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RELAXATION OF STRESSES IN METALS AND ALLOYS. (U)
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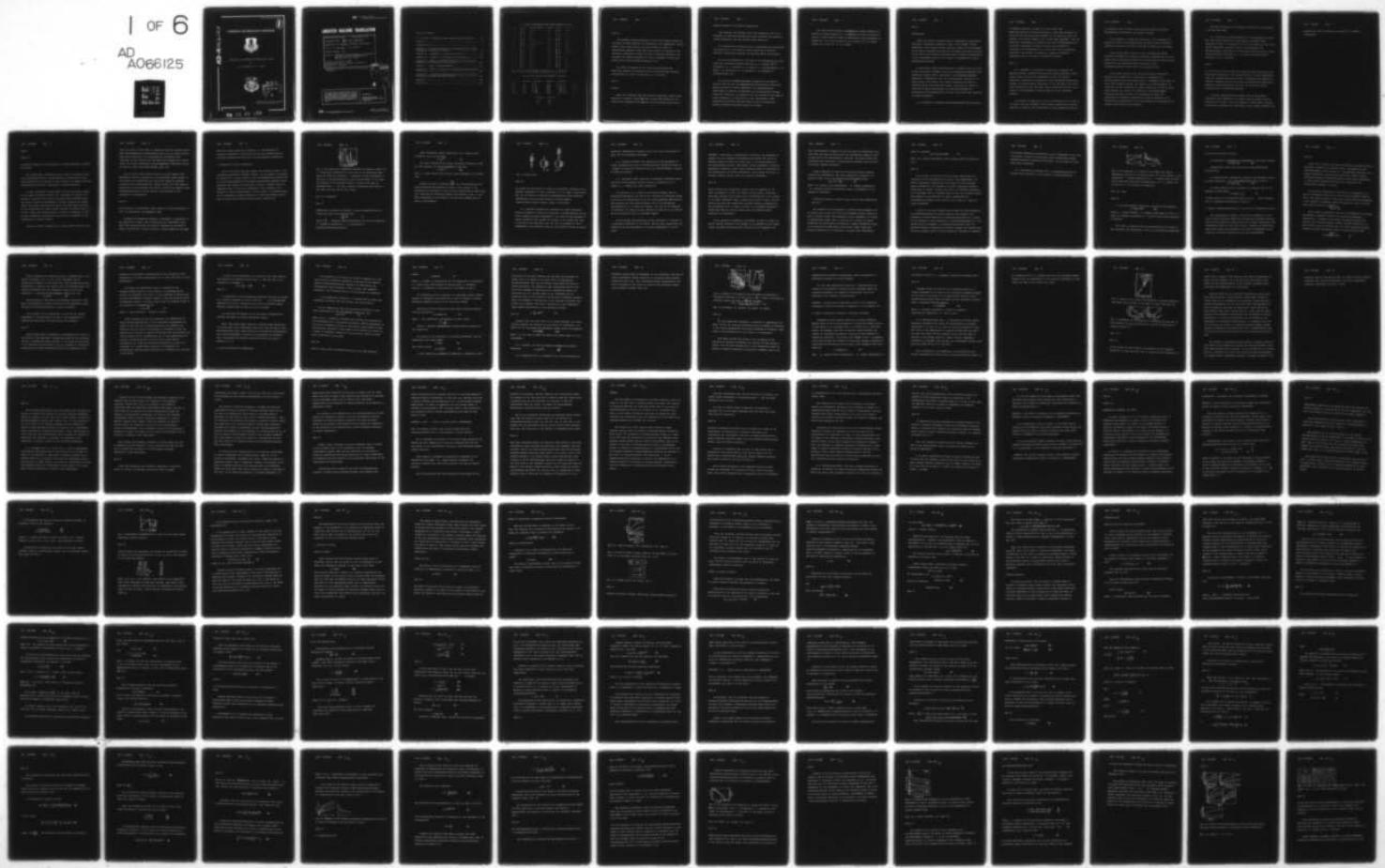
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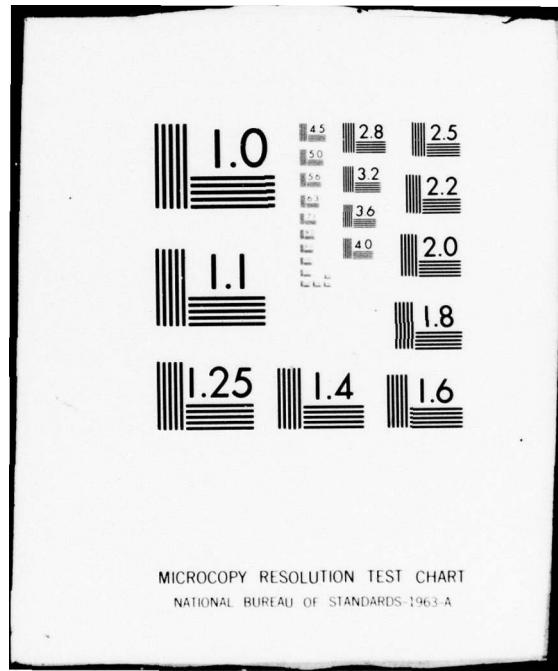
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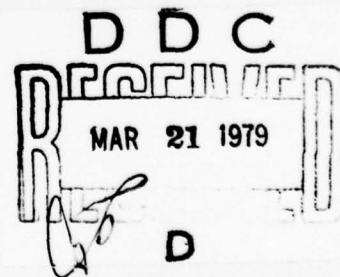
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RELAXATION OF STRESSES IN METALS AND ALLOYS

By

A. M. Borzdyka, L. B. Getsov



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By: A. M. Borzdyka, L. B. Getsov

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PREPARED BY:

TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	А а	A, a	Р р	Р р	R, r
Б б	Б б	B, b	С с	С с	S, s
В в	В в	V, v	Т т	Т т	T, t
Г г	Г г	G, g	У у	У у	U, u
Д д	Д д	D, d	Ф ф	Ф ф	F, f
Е е	Е е	Ye, ye; E, e*	Х х	Х х	Kh, kh
Ж ж	Ж ж	Zh, zh	Ц ц	Ц ц	Ts, ts
З з	З з	Z, z	Ч ч	Ч ч	Ch, ch
И и	И и	I, i	Ш ш	Ш ш	Sh, sh
Й й	Й й	Y, y	Щ щ	Щ щ	Shch, shch
К к	К к	K, k	Ь ъ	Ь ъ	"
Л л	Л л	L, l	Н н	Н н	Y, y
М м	М м	M, m	҃ ъ	҃ ъ	'
Н н	Н н	N, n	Э э	Э э	E, e
О о	О о	O, o	҂ ю	҂ ю	Yu, yu
П п	П п	P, p	Я я	Я я	Ya, ya

*ye initially, after vowels, and after ъ, ъ; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	sinh ⁻¹
cos	cos	ch	cosh	arc ch	cosh ⁻¹
tg	tan	th	tanh	arc th	tanh ⁻¹
ctg	cot	cth	coth	arc cth	coth ⁻¹
sec	sec	sch	sech	arc sch	sech ⁻¹
cosec	csc	csch	csch	arc csch	csch ⁻¹

Russian	English
rot	curl
lg	log

Page 2.

Are examined stress relaxation in metals and alloys, methods of its study and basic factors, it determining: the temperature, initial stress, time, scale factor, and also behavior of metal at nonstationary systems. Given data on the effect of alloying on the relaxation resistance of steel and other structural materials. Are developed the conditions/modes of the heat treatment of steel and alloys, that ensures maximum relaxation life.

The book is intended for the technical-engineering and scientific workers of metallurgical and machine building industry.
Illustration 114. Tabl. 45. References of 216 titles.

Page 5.

Preface.

Among the structural and heat-resistant materials, used in many branches of industry, important place occupy they stopped and the alloys (less frequently pure metals), that work under conditions of

stress relaxation at different temperatures.

For obtaining the materials with high relaxation life, it is necessary to know mechanism and basic laws governing the process of stress relaxation, and also factors, which affect it.

The conducted for last/latter years theoretical and experimental investigations in the field of stress relaxation in metallic materials considerably expanded our knowledge about this process.

The large contribution to the study of the phenomenon of stress relaxation introduced Russian scientists N. S. Kurnakov, N. N. Davidenkov, Ya. I. Frenkel', S. I. Gudkin, S. T. Konobeyevskiy, I. A. Odintsov, B. M. Rovinskiy, Yu. N. Rabotnov, L. M. Kachanov, B. Finkel'shteyn, etc.

The authors of present monograph attempted on the basis of literary this and our own investigations to critically examine the physical aspects of stress relaxation, the phenomenological dependences, the effect of structure, the interconnection between relaxation and creep. Are discussed also the methods of the study of stress relaxation, in particular at high temperatures. Vital importance the authors abstract/remove theory and practice of alloying relaxation-resistant steels and alloys.

The idea of the creation of monograph on stress relaxation in metals and alloys belongs to V. Z. Tseytlin, by whom is written to chapter I about physical nature and mechanism of this phenomenon of chapter II, III, v and partially IV are written by L. B. Getsov, chapter IV, VI and VII - A. M. Borzdyk.

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Introduction.

Under term stress relaxation usually understands a spontaneous reduction in mechanical stresses in metal (with constant linear dimensions). Such stresses either specially create with the assembly of the units of machines and units for providing the normal operation of the latter (for example, fastening joints, springy cell/elements), or they unavoidably appear in the process of manufacture of parts (technological stress).

In particular, stress relaxation can be observed with the aging of part after heat treatment, during low-temperature tempering, with alternating loading under conditions of the assigned/prescribed amplitude of deformation, etc. The investigations, carried out in recent years, they showed, that stress relaxation can occur in different metals and alloys with normal, high, and in a series of cases and at minus temperatures. Is establish/install the possibility of the decompositioin of parts, that work under conditions of stress relaxation.

It is possible to consider establish/install that relaxation

of stresses (similar to creep) it is the result both shift-dislocation and diffusion processes. First type processes are connected with the cooperative movement of the group of atoms (for example, on the shear planes, etc.). Second type processes - with the individual displacement of separate atoms both at the boundaries of the grains of basement structure and over entire volume of polycrystal. The predominant role of the other one or phenomenon, controlling the process of relaxation, depends on operating temperature and on the level of effective stresses.

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It is expedient to distinguish relaxation of stresses (in material, parts), realized via macro-creep under conditions, which impede change in the linear dimensions of part, and stress relaxation, caused by the processes of micro-creep both between the elements of microstructure (relaxation of the 2nd kind), and within them (relaxation of the 3rd kind). Stress relaxation in part can be caused by the processes of micro-relaxation in the structural elements.

The strength of materials of stress relaxation can be raised by the means: the heat treatment, which ensures optimum for relaxation resistance structure; the stabilization, which increases resistance

of relaxation (and of creep) during the first stage of process; thermomechanical treatment; by repeated loadings.

It is possible to assume that obtaining of the necessary for information about the characteristics relaxatior life of different structural materials will within the next few years go in two ways.

First, by the direct testing cf such materials for stress relaxation employing the existing procedures (including the our most widely used in laboratories method of testing rings of equal strength bending) for the duraticns, which correspond to the assigned/prescribed service lives or approaching them.

In the second place, by the application/use of calculated methods of the evaluation of resistance of relaxation (by characterizable creep with varying stress) according to test data for creep (with constant stress). For example, the characteristics of relaxation for the conditioins of single loading, as it will be shown below (Chapter II), can be with sufficient accuracy/precision calculated from the theories of strengthening or flow. The propagation of electronic computers will make it possible to use extensively for determining of the characteristics of relaxation the primary curved creep of the material.

Both these directions are legitimate ones and do not eliminate in any way each other.

so, if alloy is developed/processed or is investigated for parts, that work under conditions of rigid loading (possible stress relaxation), then it is expedient to carry out testing not for creep, but for relaxation, since the latter is considerably less labor-consuming, especially if we experience/test the rings of equal strength bending (according to I. A. Odintsov) or coiled springs (according to A. A. Chizhik).

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In the latter case the results of relaxation tests utilize even for calculated determining of the characteristics of creep. Furthermore, since the proposed calculated methods of determining resistance of repeated relaxation did not find also sufficiently wide application, conducting the corresponding tests for the evaluation of this characteristic is completely necessary.

In present monograph were reflected both of directions: experimental and analytical. Is included special chapter "stress relaxation and creep", where are examined in detail above questions touched upon. Especially is investigated cyclic stress relaxation and

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decomposition under conditicons of relaxaticn at elevated
temperatures.

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Chapter I.

On physical nature and the mechanisms of stress relaxation in metals and alloys.

The crystal body, transferred by the effect of external forces into nonequilibrium state, always attempts to return back in the equilibrium state. The process of the transition of crystal body from nonequilibrium state into equilibrium is called relaxation.

In ideal (faultless) single-crystal body all processes, caused by the effect of external forces, are reversible. But without the release of body from the action of external forces tendency toward the return to state of equilibrium in perfect crystals can realize itself only under conditions under which the atoms under the effect of the fluctuations of thermal energy overcome the energy barrier, or in such a case, when single crystal is ground to subgrains. In real crystals relaxation processes are explained by the presence of the flaws/defects of crystal lattice.

During the elastic deformation of crystal bodies with any final

rate, the level of free energy is increased and they transfer/convert into thermodynamically nonequilibrium state. Only in ideally elastic body during infinitely slow (quasi-static) deformation under conditions of low voltages will not occur the dissipation of elastic energy and elastic deformation will be completely reversible process for which is valid approximate Hooke's law: $\sigma=E\varepsilon$.

For the real crystal bodies, loaded in elastic region, this dependence, strictly speaking, it is unacceptable, since because of the presence of flaw/defects and them almost always is observed transition from thermodynamically nonequilibrium into more state of equilibrium. Such deviations from elastic behavior are usually called common/general/total term the "elastic imperfections" or the "phenomena of inelasticity".

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The processes of inelasticity, which develop in time in direction to state of equilibrium, are relaxation ones.

Relaxation processes are developed differently in dependence on the properties of body, form of deformation and conditions, under which they occur/flow/last, and they are developed in the form of elastic after-effect, internal friction, stress relaxation. Figures 1

gives the typical according to Zener [1, s. 268] spectrum of relaxation processes in solid with the very low voltages when are virtually excluded processes micro- and macroplastic deformation.

1. Phenomenon of stress relaxation.

Even in the first half past century were noted the facts of the spontaneous decrease of internal stresses. In the opinion of Poisson, in liquids for a certain period of time continuously are levelled off or are attenuate/weakened the stresses from external pressure. After extending this thought to solid ones to apes, R. Maxwell made the assumption that the drop (or relaxation) of the stresses in the function of time is proportional to stress level. It considered solid as the viscoelastic system, combining in itself the ideally elastic body of Hooke and the ideally viscous body of Newton [2].

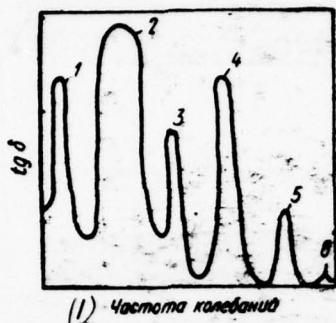


Fig. 1. The spectrum of relaxation processes according to Zener [1]:
 1 - anisotropic distribution of the pairs of the dissolved atoms under the action of stresses; 2 - processes on grain boundaries; 3 - the same, on twin/counterparts' boundary/interfaces; 4 - the same, the ordering of the dissolved atoms in alloys of the type of implementation; 5 - the same, caused by transverse heat fluxes; 6 - the same, intercrystalline heat fluxes.

Key: (1). Frequency.

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Consequently, according to Maxwell a change (relaxation) in the stress with time must follow the law

$$-\frac{d\sigma}{dt} = k\sigma, \quad (1)$$

where $k = \frac{E}{\eta}$ - constant, which characterizes the rate of relaxation;
 E - modulus of elasticity; η - coefficient of ductility/toughness/viscosity.

After integration within limits from 0 to τ under initial conditions $\tau=0; \sigma=\sigma_0$ we obtain

$$\sigma = \sigma_0 e^{-k\tau}. \quad (2)$$

The value, reciprocal k , Maxwell call, named "relaxation time" τ_0 . Then equation (2) can be presented in the form

$$\sigma = \sigma_0 e^{-\tau/\tau_0}. \quad (2a)$$

Here τ_0 - time, during which initial stress diminishes in $e=2.71828$ once.

Fig.

Besides the model of Maxwell (Fig. 2a), that consists of the series-connected cell/elements: elastic E and viscous η , for describing the processes of creep utilizes Kelvin-Voigt's model (Fig. 2b), consisting of parallel-connected cell/elements E and η , and also combinations of the models of Kelvin-Voigt, Maxwell and of elastic cell/elements.

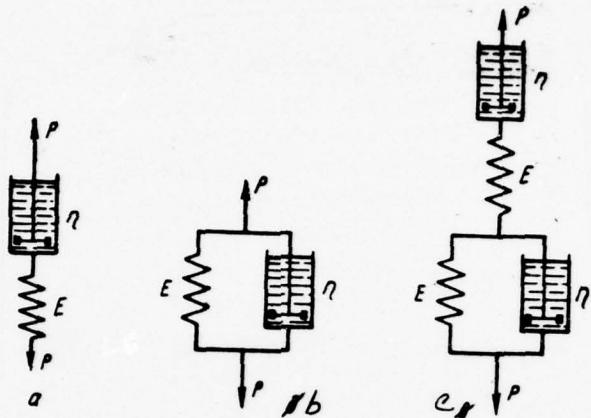


Fig. 2. Models solid.

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So, during the description of creep and relaxation, according to the combined hypothesis of creep, proposed by Ye. A. Heyn, is used model Fig. 2c. It consists of Maxwell's component/link, which describes irreversible creep, and the totality of Kelvin-Voigt's component/links, which simulate elastic after-effect.

N. S. Kurnakov examined the phenomenon of stress relaxation closely connected to nature and properties of tested material and its state. Observing during experiments on the study of flow pressure of plastic bodies [3] the process of a change in the stress with time, it arrived at the conclusion that the rate of relaxation κ (with consequently, and relaxation time τ_0) they depend not only on ambient

conditions (temperature, pressure, etc.), but also on the nature of metal and its preliminary treatment.

N. S. Kurnakov attached much importance to the phenomenon of stress relaxation and even he include/connected "relaxation time" in a number of properties, determined with the physico-chemical analysis of metals and alloys.

N. S. Kurnakov's basic ideas were subsequently developed during the study of the physical nature of stress relaxation by S. I. Gubkin, L. V. Shvedov and other researchers.

In particular, S. I. Gubkin [4] expressed thought, that in polysrystalline metall the rate of the relaxation of stresses depends on the rate of intergranular slips and intracrystalline shift/shears. This position was more lately developed and it is considerably supplemented by I. A. Oding [5]. Further, the rate of the processes of relaxation is caused not only deformation rate, but it is first of all the function of state of substance itself.

As has already been mentioned, stress relaxation - a process of a spontaneous reduction in the stress¹ in the body, placed under the conditions of the invariability of initial deformation in line of force.

FOOTNOTE 1. Under words a "spontaneous reduction in the stresses" is implied that the relaxation occur/flow/lasts without the action of external forces, and this is correct only in the ratio/relation to the technological stresses (see below). Stress relaxation in parts or assemblies of machine, placed during assembly under the conditions of the invariability of initial deformation, occurs under the action of external reacting forces, which are gradually decreased.

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These stresses can be specially created with the assembly of the units of machines or tools, for example bolted joints, cylindrical and ribbon springs, which retain their size/dimensions in the process of the works, different tight, landing/fitting and so forth, and also located ever more wide application stressed concrete, reinforced by the prestressed wire. In these all cases it is desirably possible to longer keep close to initial stress level and therefore their relaxation is undesirable.

In the process of manufacture (treatment) of parts in them, can appear residual stresses. As an example it is possible to give welded joints, tape/film coatings, parts, obtained by cold pressing, etc.

Such "technological" stresses in many instances are undesirable ones, since they can cause during service the inadmissible shaping of part or even lead to its decomposition. Therefore one should create such conditions that relaxation of technological stresses would pass with the largest possible intensity.

Stress relaxation in pure form is developed during constant initial total deformation. The basic condition of relaxation (in elastic region) can be expressed by the relationship/ratio

$$\epsilon_0 = \epsilon_y + \epsilon_n = \text{const}, \quad (3)$$

where ϵ_0 — initial total deformation; ϵ_y — elastic deformation; ϵ_n — residual (plastic) deformation, which is accumulated in the process of relaxation.

If body was loaded in elastic region, then at zero time (τ) $\epsilon_0 = \epsilon_y$, and $\epsilon_n = 0$.

The condition of the constancy of initial total deformation (3) is correct only in the case of the instantaneous primary loading of body in elastic region with subsequent stress relaxation. If loading is manufactured slowly, then in this case as a result of stress relaxation can arise plastic deformation. Plastic deformation occurs in the load case of body higher than elastic limit. Thus, more strictly condition of the constancy of initial total deformation

should be recorded

$$\varepsilon_0 = \varepsilon_y + \varepsilon_n + \varepsilon_{ns} = \text{const}, \quad (4)$$

where ε_{ns} — plastic deformation, which appears with the loading of part.

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In the course of time in the loaded body, placed under the conditions of the invariability of initial total deformation, the elastic deformation descends and with respect to this increases plastic deformation. The decrease of elastic deformation (elastic distortions of crystal lattice) will entail a reduction (relaxation) in the stresses. This is visually shown on Fig. 3a, in which is given the schematic of the decrease of elastic deformation and corresponding increase in the plastic, and on Fig. 3b — curve of stress relaxation.

A series of the laws governing the process of stress relaxation was established on single crystals. The course of the processes of stress relaxation in polycrystalline metal as a result of the presence of grain boundaries is realized/accomplished by a more complex form. For example, in polycrystalline metal under the specified power and temperature conditions appears the stressed state because of elastic shifts on grain boundaries. Therefore is possible

also stress relieving by relaxation on grain boundaries. It can occur in two ways - either by the directed atomic displacement through boundary/interfaces (diffusion plasticity), or as a result of slip along grain boundaries.

B. M. Rovinskiy [6] assumes that in polycrystalline body are possible three varieties of the process of stress relaxation:

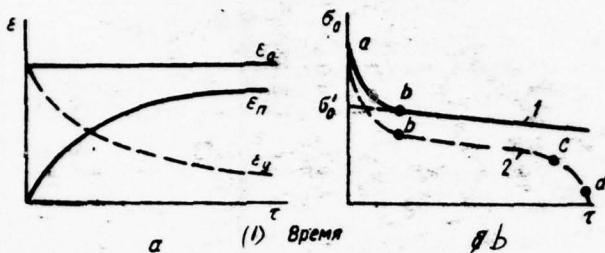


Fig. 3. The schematic of a change in the plastic and elastic deformations (a) and in the initial stress (b) in the process of the relaxation: 1 - typical dependence $\sigma-\tau$; 2 - possible form of curve for an alloy with structural transformations (a-b - I period; b-c - II period; c-d - III period of relaxation).

Key: (1). Time.

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a) the elasto-plastic relaxation, described by the equation

$$\sigma_\tau = \sigma_0 \exp [-(k\tau)^p], \quad (5a)$$

where σ_0 - initial stress; σ_τ - stress at the moment of time τ ; p - index of relaxation resistance; k - relative rate of the relaxation of stresses.

This form of relaxation occurs predominantly in the region of the relatively low temperatures, which do not exceed the temperature

of the rest (is below $\sim 0.25 T_{m\alpha}$);

b) viscoelastic deformation at boundaries of the grains (blocks)

$$\sigma_\tau = \sigma_0 \exp [-k_a \tau], \quad (5b)$$

characteristic mainly for the region of mean temperatures
 $(0.25-0.5) T_{m\alpha}$;

c) elastic-viscous deformation, caused by the diffusion current
 of atoms (vacancies) - for a high-temperature range ($>0.5 T_{m\alpha}$):

$$\sigma_\tau = \sigma_0 \exp [-k_D \tau]. \quad (5c)$$

All these equations can be considered as special cases of the
 equation of Oding-Nadai:

$$\sigma_\tau = \sigma'_0 \exp \left[-\frac{1}{t_0} \tau \right], \quad (5)$$

in which term $1/t_0$ is designated through k, k_a, k_D , and in equation
 (5a) is introduced the exponential index $p=1$.

2. Special feature/peculiarities of relaxation of stresses and creep.

The irreversible increase in the plastic deformation in time
 during stress relaxation makes this process with outwardly identical
 ones with the process of creep, during which plastic deformation also
 continuously builds up (but with $\sigma=\text{const}$). However, the conditions,
 under which occurs the accumulation of plastic deformation, during
 relaxation and creep substantially they are distinguished.

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First of all during creep under conditions of constant stress, a continuous increase in the overall (total) deformation of part (specimen/sample) occurs because of a corresponding increase in the plastic deformation. During stress relaxation, overall (total) deformation remains constant/invariable, equal initial deformation ϵ_0 , and plastic deformation increases only because of the corresponding decrease of elastic.

During stress relaxation, the process of an increase in the plastic deformation occurs within the initially stressed volume of metal. The limit for which is approached in this case the accumulated in the process of relaxation plastic deformation, this is the very small elastic initial deformation:

$$\lim_{\epsilon_n \rightarrow \epsilon_0} \epsilon = \frac{\sigma_0}{E}.$$

During creep an increase in the plastic deformation is continued continuously, sometimes reaching the significant magnitude. Furthermore, an increase in the plastic deformation occurs with constant load and approximately constant (without considering the third period) stress. Therefore under all other constant/invariable conditions plastic deformation exists a function only of time:

when
 $\epsilon_n = f(\tau)$ and $\sigma = \text{const.}$ (6)

During relaxation the effective stress is constant only at the moment of loading, i.e., at $\tau=0$, in the subsequent time it continuously descends. In the manner that during relaxation plastic deformation is caused by the stress, which are variable value, then plastic deformation with the temperature constancy and other conditions - a function of two parameters (stress and time

$$\varepsilon_n = f[\tau, \sigma_\tau]. \quad (6a)$$

The difference in the power and deformation conditions, under which occur/flow/lasts plastic creep strain and relaxation, causes the special feature/peculiarities of these processes.

In the region of mean temperatures [$(0.25-0.5) T_m$] plastic deformation is realized mainly because of the displacement of dislocations (slip along the shear planes and creeping).

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During creep plastic deformation is accumulated as a result of interaction of two processes: strengthening metal and its softening (return). Strengthening occurs because of the action of the sources of the generation of dislocations with the formation of dislocation accumulations and other obstructions. Return is explained by the

resorption of dislocation accumulations via the creeping of edge dislocations (at higher temperatures) and of dual cross slip of screw dislocations.

The section of steady-state creep is explained by the achieved/reached equality of the velocity of strengthening and velocity of softening. The sources of the generation of dislocations act with approximately constant intensity, since the acting at given torque/moment stress σ is always greater than the breaking stress of the generation of dislocations σ_{kp} :

$$\sigma > \sigma_{kp} = \frac{Gb}{l}, \quad (7)$$

where G - shear modulus; b - Burgers's vector.

During relaxation occurs the exhaustion (or "depletion") of easily movable dislocations. At each subsequent torque/moment the stress is less than into preceding/previous, and therefore the effective force of sources continuously is decreased in time. The decrease of the density of mobile dislocations and their bonding into stable systems lead to strengthening. But at high temperatures the intensity of softening due to creep and dual cross slip of dislocations (at constant/invariable temperature) is proved to be increased. As a result under conditions of relaxation, the strengthening insignificantly depends on the intensity of a reduction in the stress.

A series of the researchers (I. A. Oding et al.) they identify the intensity of softening during creep I_c with the rate of the relaxation of stresses v_r :

$$I_c = v_r = \frac{d\sigma}{d\tau} = -E \frac{de}{d\tau}. \quad (8)$$

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In proportion to the approach/approximation of stress and caused by its elastic deformation to zero ($\sigma \rightarrow 0; \epsilon_y \rightarrow 0$) the thermodynamic equilibrium of body is restored and the level of internal energy descends. During creep of this, it is not observed.

Are such basic differences in the processes of relaxation of stresses and creep (in average temperature range).

Metal, that works under conditions, calling stress relaxation, is located under less advantageous conditions, than the metal, which experience/tests creep, since during stress relaxation strengthening from plastic deformation in view of its limitedness is extremely small. Confirming this position experimental data are given in Chapter IV, p. 4.

3. Stress relaxation and temperature.

The character of the increase of plastic deformation in time during creep in different temperature intervals has the specific special feature/peculiarities. Depending on temperature, are distinguished three varieties of this process. This approach, apparently, can be extended also to the phenomenon of relaxation.

1. Low-temperature relaxation - at temperatures is lower than temperature of return (for pure metals lower than 0.25 T_m).

In this temperature range the deformation increases in time, being subordinated to the approximately logarithmic law:

$$\epsilon = \alpha \ln \tau + \beta, \quad (9)$$

where α and β - constants. Therefore very process of an increase in the deformation can be call/named logarithmic. Plastic deformation in this case is explained by glide of dislocation along planes of shear. Strengthening, according to Mott-Nabarro and Cottrell [7], occurs as a result of continuous exhaustion of dislocations, which are found under conditions of easy glide.

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Based on this, plastic deformation depends on the time following

manner:

$$\varepsilon = nFbkT \ln \lambda \tau, \quad (10)$$

where n - a number of dislocations per the energy unit of activation; F - average area, free/released by dislocations; b - Burgers's vector; λ - frequency of dislocations at the moment of time τ .

The relaxation, which corresponds to logarithmic region, weakly depends on temperature and completely it does not depend on stress. Deformation depends linearly on the activation energy.

Feltam [8] for this temperature range gives following equation of stress relaxation:

$$\Delta\sigma = S_r \lg(1 + \gamma\tau), \quad (11)$$

where γ - the coefficient, not depending on time τ and S_r :

$$S_r = \frac{d\sigma}{d \lg \tau}.$$

Value S_r descends approximately linearly with an increase in the temperature.

The energy of the activation of relaxation determines from the dependences: with shear stress

$$Q = \frac{kT}{S_r} \Delta\tau; \quad (12)$$

with tensile stress

$$Q = 2,3 \frac{kT}{S_r} \Delta\sigma. \quad (12a)$$

2. Mean temperature relaxation is observed in temperature range

[$(0.25-0.5) T_m$], by which actively are developed the processes of return, but it is nearer to the upper level of temperatures - recrystallization. The basic processes, which check the course of stress relaxation, the creeping of edge dislocations and the dual cross slip, because of which occurs the softening of metal; all last/latter all to a lesser degree we can compensate for the weakening action of the sources of dislocations. Diffusion processes cause the creeping of dislocations of one (blocked) slip plane into another (not blocked). The rate of relaxation in this temperature range depends exponentially on the activation energy:

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$$v_r = \frac{d\sigma}{d\tau} = Ge^{-Q/RT}. \quad (13)$$

However, thus far still there is no unified opinion, as to more rightly determine the energy of the activation of relaxation, L. P. Nikitin [9] it calculates the activation energy, using the dependence

$$\tau_0 = A_0 \exp \frac{Q}{RT}, \quad (14a)$$

where τ_0 - the time in which the stress will become equal to σ ; A_0 - coefficient.

P. I. Aleshkin [10] for this purpose utilizes the analogous dependence

$$\tau_0 = A_0 e^{-Q/RT} \quad (14b)$$

G. N. Kolesnikov and A. P. Moiseyev [11, s. 101] determine the

activation energy from the dependence of the logarithm of the rate of plastic deformation during relaxation on reciprocal value absolute temperature (Fig. 4a). They establish/installled experimentally that with an increase in the stress the value of the activation energy passes through a maximum (Fig. 4b).

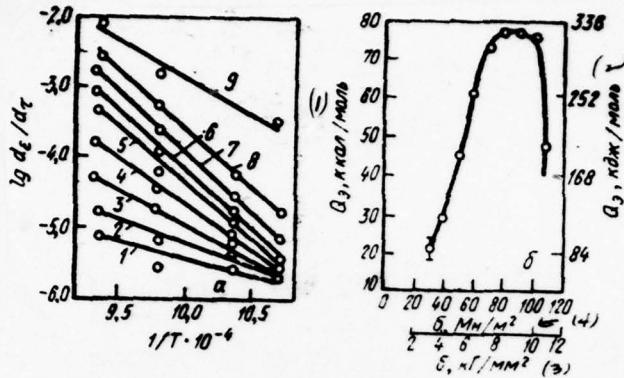


Fig. 4. Change in the energy of the activation of relaxation Q_0 , calculated according to by the curve $\lg \left(\frac{d\epsilon}{dt} \right) - 1/T(a)$, as function of effective stress $\sigma(b)$ with $\sigma_0, \text{MN/mm}^2 (\text{kg/mm}^2)$:

1 - 300(30); 2 - 400(40); 3 - 500(50); 4 - 600(60); 5 - 700(70); 6 - 800(80);
7 - 900(90); 8 - 1000(100); 9 - 1100(110)

Key: (1) kcal/mole. (2) kJ/mole. (3) kg/mm². (4) MN/mm².

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3
 3. High-temperature relaxation is observed at temperatures (is above $\sim 0.5 T_{nn}$), by which are promoted/activated processes of diffusion. In this region predominates the vacancy mechanism of diffusion, which leads to the acceleration of the creeping of dislocations.

With small stresses the energy of the activation of the migration of vacancies determines the intensity of the process of strain. With the high stresses also in this temperature range the strain is caused by movement of dislocation. However, this is not

accompanied by noticeable strengthening, since the majority of dislocations emerges to crystal boundary.

For very high temperatures ($>0.5 T_{m\alpha}$) is characteristic the totality of the diffusion processes (which seemingly create the prerequisite/premises of movement of dislocation) and of the processes of the creeping of dislocations¹.

FOOTNOTE 1. In more detail temperature effect on the relaxation resistance of metals and alloys is examined on p. 4 of Chapter IV.

4. Bases of relaxation resistance of metallic materials.

Resistance of the metallic materials of stress relaxation depends first of all on the strength of the bonds in crystal lattice of base metal. B. M. Rovinskiy and V. G. Lyuttsa [12, p. 285] they showed, for example, that than "is harder" crystal lattice, the greater the relaxation resistance of metals. As the criterion of relaxation resistance, is utilized value $R=(1/p)-1$. Here p - parameter, which characterizes the intensity of relaxation process, depending on composition and structural state of metal. This parameter find their equations

$$\epsilon_t = \epsilon_0 \exp [-(k_1 t)^p], \quad (15)$$

where ϵ_0 — initial elastic deformation; ϵ_t — elastic deformation at

the moment of time τ ; k_1 - parameter, determined by stress level.

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Figure 5 gives the found by E. M. Rovinskiy and to V. G. Lyuttsa dependence of the index of the relaxation resistance $R=(1/p)-1$ on the value of the square of the quasi-elastic force K^2 , which characterizes binding forces in crystal lattice (rigidity of grage). Value K determines from the equation

$$K = 4\pi^2 \frac{k^2}{h^2} m\theta^2, \quad (16)$$

where k - Boltzmann constant; h - Planck's constant; θ - characteristic temperature; m - mass of atom.

Z. N. Petropavlovskaya and I. A. Sacherkova [14] also connect relaxation resistance with value $m\theta^2$, proportional to stiffness coefficient K . On Fig. 6a, is given the plotted according to their data curve of the dependence of a relative voltage drop for 1000 h (at 20°C) from value $m\theta^2$ for aluminum, copper and iron. With an increase of the binding forces in crystal lattice, relaxation resistance is increased, but straight-line relationship between ratio $\Delta\sigma/\sigma_0$ and value $m\theta^2$ it is not detected.

With an increase in the temperature, the intensity of the thermal oscillations of atoms (ions) in crystal lattice increases. B.

M. Rovinskiy and to V. G. Lyuttsa with this they precisely connect decrease with the temperature of the relaxation resistance of pure nickel and some of his alloys [12, p 285].

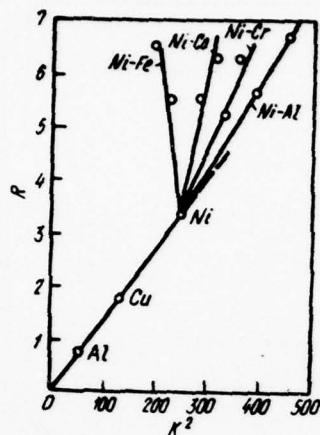


Fig. 5. Change in the index of the relaxation resistance $R = (1/P) - 1$ some metals and of alloys on the basis of nickel from value K^2 .

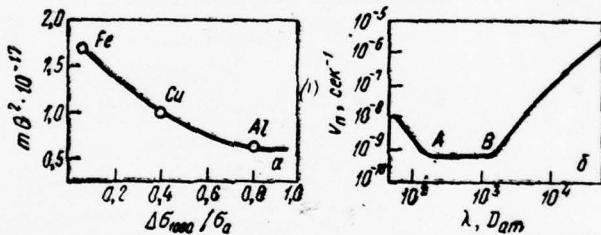


Fig. 6. Dependence of the intensity of relaxation on value $m\theta^2$ (a) and intensity of creep from distance λ between the particles of dispersed phase (b).

Key: (1) s.

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In the opinion of these authors, the decrease of the relaxation resistance of these materials with an increase in the temperature is

caused only by change of the energy of the thermal oscillations of atoms in grate. However, as can be seen from later works, basic effect has the intensification of the diffusion processes, which facilitate the displacement of dislocations.

Important value for the relaxation resistance of pure metals have packing defects. If body-centered crystal (BCC) lattice of α -iron, there are no foundations for expecting a large quantity of extended dislocations, but in γ -iron and nickel and especially in solid solutions on the basis of these metals, which possess the face-centered (FCC) grate, dislocation, as a rule, they are split. Therefore all processes, connected with the development of plastic deformation, in α -iron are intensified with an increase in the temperature in considerably larger degree. In connection with this for α -iron and its alloys, the relationship/ratio between maximum operating temperature and melting point ($^{\circ}$ K) is approximately equal to 0.48; for γ -iron and its alloys 0.59; for nickel and its alloys 0.68.

The strength of communication/connections of crystal lattice of pure metals can be changed by alloying with the cell/elements, which form substitutional solid solutions, as it was shown to V. A. Il'inoy and V. K. Kritskoy [15, p 412]. The majority of such cell/elements, for example cobalt, molybdenum, manganese, niobium, increases in the

increasing order of the binding force of ferrite and only vanadium decreases them. Chromium in quantity 2-80/c also considerably reinforces interatomic bonds [15, p 408].

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The available experimental data [14] confirm that resistance of ferrite of relaxation and creep they increase chromium, molybdenum, cobalt and tungsten. In this case, the greatest effect is reached at the multiccomponent alloying (see Chapter VI, p. 2). The alloying of iron with nickel in the quantity necessary for the formation of stable at room temperature austenitic structure, to a considerable degree increases the relaxation resistance of iron. The alloying of alloys Fe-Ni with the cell/elements, which increase the strength of connections (by chromium, by tungsten, by molybdenum, etc.), contributes to further increase in the relaxation resistance.

G. V. Kurdyumov and N. I. Travin [15, s. 402] by radiographic investigation established that in solid solutions on the basis of nickel the introduction of additions of chromium, titanium and of aluminum leads to an increase in the forces of interatomic bonds in with the fact of larger degree, the higher the concentration of these cell/elements (within the investigated limits, which do not exceed their critical solubility by nickel at room temperature).

However, the role of the alloying cell/elements (locating in the dissolved form in base metal) in an increase in the relaxation resistance consists not only in an increase in the forces of interatomic bond. The dissolved cell/elements also affect the rate of return first of all because they block thresholds and impede the creeping of dislocations. Furthermore, the atoms of the dissolved cell/elements create "clouds" (Cottrell's atmosphere) on packing defects, changing their energy. During the decrease of energy of packing defect, the creeping or the cross slip of dislocations becomes hindered/hampered. This phenomenon is known as the segregation mechanism of Suzuki. The effect of the dissolved cell/elements can be retained to relatively high temperatures.

The alloying cell/elements, dissolved in metal, affect the rate of diffusion and self-diffusion in solid solution and from this side also exert the influence on the development of plastic deformation at high temperature.

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Large heat resistance and relaxation resistance of austenitic steels and alloys in comparison with ferrite ones is caused

considerably (on several orders) by the lower speed of the diffusion of the majority of the alloying cell/elements in γ -iron, than in α -iron.

The ability of dissolved elements to increase the forces of interatomic bond and to retard of diffusion acquires large role at the very high temperatures, which exceed $0.7 T_{m\alpha}$, when plastic deformation occurs mainly because of the oriented diffusion of atoms and vacancies. The alloying cell/elements, dissolved in metal, change the conditions of its recrystallization. Already small quantities (hundredth and tenths of percentage) of some impurity/admixtures increase the temperature of the beginning of recrystallization t_p^H at the high degrees of deformation (50-60%) and prolonged annealing [16]. This effect of small ones addition is explained by the fact that the clouds of the dissolved atoms around dislocations prevent their displacement.

An increase in the concentration of the dissolved cell/element to several percentages and no longer affects value t_p^H . If the alloying cell/element, introduced into metal, raises the strength of interatomic bonds, then t_p^H increases. However, the intensity of the effect of admixed atoms with high concentrations is considerably weaker than with small ones, and an increase in value t_p^H , arriving on 10% (at.) of the added cell/element, is gradually decreased. For

single-phase solid solutions on the basis of nickel, iron and other metals the value of ratio $T_p:T_{\text{rec}}$ can be raised because of an increase in the interatomic bonds only to 0.5-0.55 [16]. The higher temperatures of the beginning of recrystallization can be obtained in heterophase alloys.

An increase in the temperature of the recrystallization of alloy expands the temperature interval in which most effective possible resistance of stress relaxation. Therefore the solid solutions, formed by the alloying cell/elements, which increase the temperature of the beginning of recrystallization, retain relaxation resistance to higher temperatures.

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However, great resistance of stress relaxation (just as creep) we can be reached only if the concentration of the alloying cell/elements exceeds their critical solubility in base metal at operating temperatures and surplus quantities of these cell/elements are separated with the formation of the particles, which delay of the displacement of dislocations.

Dislocations can be braked by the zones of preseparations, forming in crystal lattice releasing phases, even coherent with

matrix solid solution and isolated particles of the excess phases of different degree of dispersion. In this case, the important value has a distance between such obstructions [7, 8]. If the distance between obstructions L is small in comparison with the maximum radius of curvature of dislocation $r_c = \frac{\sigma_b^*}{\tau}$ in stress field σ , then dislocation with Burgers's vector b during displacement on the plane of slip barely is bent.

FOOTNOTE 1. Here τ - force of surface tension. ENDFOOTNOTE.

This, for example, occurs, when as obstructions serve the isolated/insulated atoms of cell/elements in solid solution.

But if isolation are located in the form of large particles, far distant one from another ($L > r_c$), as in the averaged alloy with the high degree of the coagulation of particles, then dislocation passes between particles.

Great braking to movement of dislocation is observed in the intermediate case when $L \approx r_c$ (very dispersed isolation; the particles, coherent with basic solid solution; the zone of Guignet - Preston).

What driving/moving with rate dislocations are stopped by the

particles of isolation; they can overcome these obstructions either via creeping or via the cross slip in order to pass past obstructions or between them. But the particles of isolation, if they are sufficiently solid and stable, can fasten the driving/moving dislocations, preventing their slip and creeping.

Mak Lin by calculation established the numerical ratios between creep rate and distance between centers of the particles of strengthened/hardened phase [17] (see Fig. 6b). In this case, it was assumed that the dislocation density and the rate of their creeping were such, that they lead to the observed in technology creep rates.

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With small distances between the particles (left branch of the curve) dislocations cannot overcome the particles, but, probably, they will intersect them or "to force" through matrix/die. With the very large distances between particles (right branch of the curve), when in the interval between it can contain itself several dislocations, their creeping it occurs simultaneously, that also causes an increase in the creep rate. On the horizontal section AE, the creep rate does not depend on the distance between particles, since during its increase proportionally grow/rises and particle size, in consequence of which relative value of free path for movement of dislocation it is not

changed.

The high degree of dispersion of particles retards of creep as a result of the fact that it strongly retards of return. The presence cf dispersed isolation has noticeable effect also on the course of recrystallization in alloy. On the basis of S. S. Gorelik's data [16], a large number of dispersed particles of carbide and other isclation can considerably raise the temperature of the beginning of recrystallization and increase $T_p:T_{\text{ex}}$ to ~0.8.

The particles of excess phases, being located in finely dispersed state, block the nuclei cf recrystallization, preventing their growth. The processes of recrystallization hinder as a result cf the fact that the particle of the phases of the isolation whose specific volume differs frx the vclume of matrix/die, they can be located in the state of precipitation hardening. In heterophase alloys the process of recrystallization is divide/mark off as into two separate processes: origin/conception/initiation and increase in the nuclei of recrystallization. The temperature " T_p " in the supersaturated solid sclutions is actually the temperature of an intense increase in the nuclei of recrystallization. Specifically, with this temperature is connected noticeable softening of such alloys.

The more thermostable ones are the particles of isolation, the higher lowest temperature of recrystallization t_p^R and the higher relaxation life of alloy.

In order to inhibit stress relaxation, the particles of isolation must not be highly dispersed ones, but also long retain high degree of dispersion.

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Entangled dislocation networks, that are formed as a result of the displacement of dislocations in different directions, are low-mobility and, furthermore, they will be delayed effectively by finely dispersed particles. Metal with this structure stable resists return, creep and stress relaxation.

Cottrell [7] indicates that the rate of creep strain can be estimated by the ratio/relation to the rate of return r to the coefficient of strengthening h : ($\dot{\epsilon}_n = \frac{r}{h}$). Stable dispersed particles have powerful effect on the rate of return r .

During stress relaxation in the temperature range in which actively are developed the processes of return, this it has high value, since strain hardening and, consequently, also the coefficient

of strengthening h, as it was shown earlier, considerably less than during creep.

The stability of the sizes of the particles of the excess phases, the determining intensity of the softening of alloys, to a considerable degree depends on the nature of these phases. Then are thermally more stable excess phases, by the fact less actively continue the metabolic processes between the phases of isolation and matrix solid solution [18, 19].

Especially one should stop at the role of the fine/thin (block) structure of metal. Such parameters of fine structure as the size/dimension of subgrains, the angle of their disorientation and the degree of the blocking of dislocation boundary/interfaces, have specific effect on the creep strength and relaxation of stresses [20]. The formation of specific dislocation structure with a large number of evenly distributed internal dislocation barriers is the essential factor, which hinders relaxation micro- and the macrostresses (such processes in the following presentation we will call respectively micro- and macro-relaxation).

It is established, that more prolonged resistance of relaxation of stresses and creep at elevated temperatures possess the metals and alloys with polygonal structure [21]. This is explained by

the fact that with polygonization in the structure of metal are formed the stable dislocation walls, in particular if the dislocations are blocked by foreign atoms [22, s. 65]. In this case, the important value has a degree of homogeneity of polygonal structure in the given volume of metal.

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In connection with that presented the practical methods of the creation of optimum dislocation structures of relaxation resistant alloys in connection with deserve close attention. This the methods, which consist in special deformation-thermal treatment, are examined in Chapter VII, p. 3.

Thus, the relaxation resistance of the alloys, intended for a work in the "average/mean" range of temperatures (from 0.25 to $0.5 T_{m}$), is determined.

1) by atomic-crystalline structure and type of crystal lattice of base metal. For example, alloys on the basis of α -iron with BCC by grade possess effective relaxation rate to 600°C , alloys on the basis of γ -iron with FCC by grade - to 700°C , and alloys on the basis of nickel - to 800°C .

2) with the content of the alloying cell/elements, which form with base metal stable solid solutions and which facilitate an increase in the forces of interatomic interaction and temperature it began recrystallization¹.

FOOTNOTE¹. The effect of alloying on the relaxation resistance of different alloys is examined in Chapter VI. ENDFOOTNOTE.

3) by heterophasal nature of alloys. In the alloy must be included the cell/elements, which form thermally stable joints, the capable ones long time of retaining coherence with basic solid solution is possible to more slowly coagulate.

4) by the fine/thin (block) structure of metal, which forms the internal dislocation barriers, which prevent movement of dislocation, and, in particular, by the presence of polygonal structures².

FOOTNOTE². The role of structure factor in the process of stress relaxation is described in detail in chapter VII. ENDFOOTNOTE.

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Chapter II.

RELAXATION OF STRESSES AND CREEP.

By creep, according to A. A. Il'yushin's proposition [23], is understood the phenomena of change in time of the strains and stresses, which appear as a result of the loading of part. In technical literature a change of the strain with time is called strictly creep or aftereffect, and a change in the stresses - by relaxation. Creep strain in turn, they divide into reversible and irreversible. Utilizing a term "aftereffect", is distinguished elastic and relaxation, moreover relaxation is usually considered irreversible.

In 1968 Ya. S. Gintsburg [24] proposed the new terminology, demarcating the processes of creep during the limited and unlimited overall strain and these caused processes changes in the stresses. Creep during the unlimited overall strain is named it "unlimited creep", during the limited overall strain - "limited creep". The author distinguishes three versions of limited creep depending on the character of changes in the effective stress: relaxation (decrease),

accumulation¹ (increase) and invariation (constancy) of stresses.

FOOTNOTE 1. Term "accumulation of stresses" answers the conventional concept of negative stress relaxation. ENDFCCTNCTE.

Thus, the process of stress relaxation is treated by Ya. S. Gintsburg as limited creep only with decreasing in time stress. This contradicts at present the single approach accepted, which makes it possible to examine different special feature/peculiarities of the behavior of material under conditions of constant or insignificantly changing of the overall deformation (with not absolutely rigid loading).

Real/actually, the equation, which describes creep during the assigned/prescribed overall strain, in general form

$$\begin{aligned}\epsilon_0 = \epsilon_y + \epsilon_{nn} + \epsilon_n + \epsilon_c &= \frac{\sigma(\tau)}{E}(1+cE) + \\ &+ \epsilon_{nn} + \epsilon_n(\tau, \sigma) + \epsilon_c(\tau, \sigma)\end{aligned}\quad (17)$$

makes it possible to consider only not developing in time processes of pure creep, but also strain because of structural changes ϵ_c , which to separate/liberate is experimentally difficult. In the case of the structural changes, calling the decrease of volume, $\epsilon_c < 0$; but if structural processes they are accompanied by an increase in the volume, then $\epsilon_c > 0$.

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Subsequently, examining the processes of creep with constant and varying stresses, by creep strain ϵ_m we will understand, as a rule, sum of the strains strictly of creep and structural component.

The portion/fraction of creep strain, which corresponds to reversible component, after the unloading of specimen/sample is decreased in the course of time τ (Fig. 7) -

Real/actually, if we at certain moment of time unload specimen/sample at testing temperature, the decrease of strain at the initial moment will prove to be equal to elastic deformation ϵ/E (BC); then it will proceed with the decreased rate (CD), which depends from initial stress, accumulated creep strain, time and temperature. When $\tau \rightarrow \infty$ reversible component becomes equal to zero.

The phenomenon of the decrease of accumulated creep strain in time is usually called "reverse aftereffect" or by "reverse creep". In experiences in Johnson [25] was establishinstalled the linear dependence of the deformation of reverse aftereffect on initial stress.

For describing the curves of creep with constant stresses, is proposed a series of the equations

$$\varepsilon_n = B_1(\tau) F(\sigma), \quad (18)$$

$$\varepsilon_n = Q_1(\sigma) \Psi + Q_2(\sigma) \tau, \quad (19)$$

where Ψ - certain function of stress and time; $B_1(\tau)$ - certain function of time; $F(\sigma)$, $Q_1(\sigma)$, $Q_2(\tau)$ - some functions of stress.

Dependence (19) assumes that the curves at the first (being unsteady) stage are geometrically similar, and to the second linearly they depend on time τ .

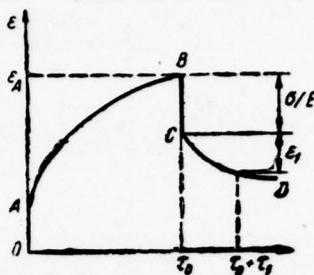


Fig. 7. Diagrammatic representation of curve of creep with reverse aftereffect during unloading.

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Unlike formula (19) expression (18) assumes the similarity of curves of creep for all extent elongation. For Q_1 , Q_2 and Ψ are proposed the following dependences:

$$Q_1(\sigma) = A\sigma^k; \quad (20)$$

$$Q_2(\sigma) = B\sigma^m; \quad (21)$$

$$Q_3(\sigma) = Be^{m\sigma}; \quad (22)$$

$$Q_4(\sigma) = B \operatorname{sh}(m\sigma); \quad (23)$$

$$\Psi = 1 - \exp[-C(\sigma)\tau] \quad (24a)$$

$$\Psi = \ln \left[1 + \frac{\tau}{C(\sigma)} \right], \quad (24b)$$

where A , B , k , m - the constants, which depend on the temperature whose value different for $\sigma < \sigma_{kp}$ and $\sigma > \sigma_{kp}$ (σ_{kp} - the stress, which corresponds to break on the curves of the dependence of the maximum speed of creep on stress, which virtually corresponds to elastic limit σ_y).

In the simplest case of the constant velocity of creep, they set/assume $Q_1=0$.

In the general case of creep, however, in the course of time are changed both the strain and stress. For the analytical description of the processes of creep with varying stress on the basis of data, obtained with constant stresses, can be used the most general theory of creep, which connects creep rate with stress, temperature and certain number of structural parameters in number of which can enter time, accumulated creep strain, instantaneous plastic deformation, prehistory of loading and so forth [27]:

$$\dot{\epsilon}_n = F(\sigma, T, \tau, \epsilon_n, \epsilon_{nn}, q_1, q_2, \dots, q_n), \quad (25)$$

where q_1, q_2, \dots some structural parameters.

However, the use of general theory is virtually impossible due to difficulties in the establishment of the form of the function F . Therefore was proposed a series of the particular theories number of which includes: 1) the theory of aging [26, 27]; 2) the theory of flow [28, 29]; 3) the theory of strengthening [27, 28]; 4) the theory of plastic heredity [27]; 5) combined theories [30-32]; 6) theory with structural parameters [33, 34].

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The experimental check of the validity of hypo-those these, for example, by the comparison of the calculated and empirical curves of relaxation, many carried out in investigations [27, 28, 35, 36], still did not make it possible in the general case to give the preference of any of the theories indicated above.

1. Theories of creep.

Theory of aging.

After assuming that with varying stresses creep strain is determined only by time and stress at given torque/moment, we will obtain the fundamental equation of the theory of the aging

$$\epsilon_n = f(\sigma, \tau), \quad (26)$$

the describing behavior of material at constant temperatures. The physical essence of the theory of aging consists under the assumption about the fact that accumulated creep strain under conditions of the application of the assigned/prescribed load is unambiguously determined by the structural state of metal. In connection with this the theory of aging considers the structural changes, which occur in metal during operation, and considers them determining that and it is basic contradiction to theory.

The theory of aging proves to be unsuitable for description creep with sharply alternating loads. Real/actually, from this theory it follows that the decrease of load to zero leads to the complete disappearance of accumulated creep strain. Furthermore, a sharp increase in the stress in the process of testing causes the formation of the very considerable instantaneous deformation, which corresponds to a difference in accumulated at the moment of time τ creep strains. The theory of aging, it goes without saying, does not describe also reverse creep and effect of preliminary instantaneous plastic deformation.

Theory of flow.

The theory of flow is instituted on the assumption that the creep rate is unambiguously determined by stress and time, i.e.,

$$\dot{\epsilon}_n = f(\sigma, \tau). \quad (27)$$

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The theory of flow just as the theory of aging, is structurally sensitive; however, it is free from the number of deficiencies by the latter. The theory of flow also does not describe reverse creep and

effect of preliminary instantaneous plastic deformation.

There are various forms of equations of the theory of flow. Thus, for instance, for the separate description of the stages of the steady and transient creep is utilized the expression

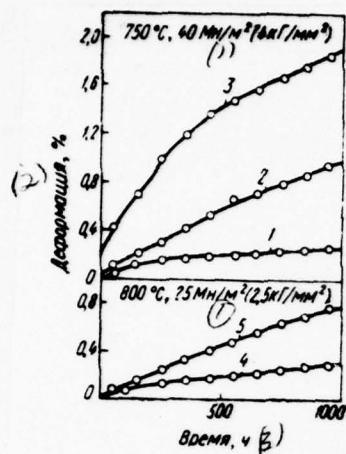
$$\dot{\epsilon}_n = Q_1(\sigma) \frac{d\Psi(\sigma, \tau)}{d\tau} + Q_2(\sigma). \quad (27a)$$

Theory of strengthening.

According to the theory of strengthening, the creep rate unambiguously is determined accumulated by creep strain and by stress:

$$\dot{\epsilon}_n = f(\epsilon_n, \sigma). \quad (28)$$

The theory of strengthening assumes that in the process of creep test occurs strengthening material, determined only accumulated by creep strain.



Key: (1) - MN/mm² (4 kg/mm²). (2) - Deformation. (3) - Time, h.

Fig. 8. Curves of creep of steel X23M18 at 750 and 800°C in initial state (1, 4) and after prolonged aging (2, 3, 5):

Номер кривой (1)	Старение (2)	$\sigma, \text{ MN/mm}^2$
1	-	$1.9 \cdot 10^{-4}$
2	750°C, 2000 $\text{h}^{\frac{1}{3}}$	$9 \cdot 10^{-4}$
3	750°C, 5000 $\text{h}^{\frac{1}{3}}$	$1 \cdot 10^{-3}$
4	-	$24 \cdot 10^{-3}$
5	800°C, 5000 $\text{h}^{\frac{1}{3}}$	$6 \cdot 10^{-4}$

Key: (1) - Number curved. (2) - Aging. (3) - h.

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Different structural changes, which occur during testing (isolation

or dissolution of the strengthened/hardened phase, recrystallization, coagulation of dispersed phase, leading to the softening of material), by the theory of strengthening are not considered.

Thus, for instance, prolonged holding with low voltages, calling structural changes in the material and leading to change creep strength (Fig. 8), during the use of theory of strengthening for the evaluation of creep rate with the subsequent increase of stress are not considered, if during testing with low voltages it was not accumulated any noticeable creep strain.

The theory of strengthening, just as the theories of aging and flow, does not describe reverse creep and effect of preliminary instantaneous plastic deformation.

Theory of plastic heredity.

Unlike the theories of aging, flow and strengthening, the theory of plastic heredity considers the prehistory of loading.

Widest use for describing creep of metals obtained the generalization of the equations of the theory of heredity to the case of nonlinear creep in the formulation of YU. N. Rabotnova:

$$\varphi(\varepsilon) = \sigma(\tau) + \int_0^{\tau} K(\tau - \tau^*) \sigma(\tau^*) d\tau^*, \quad (29)$$

where $\varepsilon = \varepsilon_y + \varepsilon_m + \varepsilon_n$ - full/total/complete deformation; $K(\tau - \tau^*)$ - the nucleus of aftereffect, characterizing the measure of effect on the deformation of the unit stress, which acted during unit time interval at earlier torque/moment τ^* .

Integral in expression (29) is the sum of voltage influences σ indicated at the different moment of time $[\varphi(\varepsilon)]$ - the stress, found from the curve of instantaneous deformation during full/total/complete deformation ε . Real/actually, if aftereffect time τ is small, integral is equal to zero and we have equation of the curve of instantaneous deformation.

$$\sigma = \varphi(\varepsilon). \quad (30)$$

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Expression for the nucleus of aftereffect can be found from experiments to creep with constant stresses.

Then

$$\varphi(\varepsilon) = \sigma + \sigma \int_0^{\tau} K(\tau - \tau^*) d\tau^*.$$

After designating

$$\int_0^{\tau} K(\tau - \tau^*) d\tau^* = G(\tau), \quad (31)$$

we will obtain

$$\sigma(\tau) = \frac{\varphi(\varepsilon) - \sigma}{\sigma} = \frac{\sigma + \varepsilon_n(\tau) E(\tau)^* - \sigma}{\sigma} = \frac{\varepsilon_n(\tau) E(\tau)^*}{\sigma}, \quad (32)$$

where E^* - tangent modulus.

When $\varphi(\varepsilon) < \sigma_y$ we have $E^* = E$. For materials with the linear strengthening $E^* = \text{constant}$, time-independent. Then the nucleus of aftereffect can be found by differentiation of equation (31) with the substitution of formula (32): $K(\tau - \tau^*) = \frac{1}{\sigma} \left\{ \dot{\varepsilon}_n(\tau - \tau^*) E^*(\tau - \tau^*) + \right. \\ \left. + \varepsilon_n(\tau - \tau^*) \frac{\partial E(\tau - \tau^*)}{\partial \tau} \right\}. \quad (33)$

The theory of plastic heredity makes it possible to describe the phenomenon of reverse creep.

During testing under conditions of constant stress at torque/moment before unloading from (29) we have

$$\varphi(\varepsilon) = \sigma_0 [1 + G(\tau_0)].$$

At torque/moment $\tau_0 + \tau_1$

$$\begin{aligned} \varphi &= \sigma_0 \int_0^{\tau_1} K(\tau_0 + \tau_1 - \tau^*) d\tau^* = \\ &= \sigma_0 [G(\tau_0 + \tau_1) - G(\tau_1)]. \end{aligned} \quad (34)$$

During the unloading

$$\varphi - \varphi_A = E(\varepsilon - \varepsilon_A). \quad (34a)$$

The strain of reverse creep ϵ_1 (see Fig. 7) [from expressions (34) and (34a)] is proved to be equal to

$$\epsilon_1 = \epsilon_A - \frac{\sigma_0}{E} - \epsilon = \frac{\sigma_0}{E} [G(\tau_0) + G(\tau_1) - G(\tau_0 + \tau_1)]. \quad (35)$$

The examination of equation (35) shows that ϵ_1 is symmetrical relative to the torque/moments of time τ_0 and τ_1 and proportional to stress σ_0 . These conclusions are confirmed experimentally in works [25, 32].

When $\tau \rightarrow \infty$ creep strain is proved to be completely reversible: $\epsilon_1 = \epsilon_A - \frac{\sigma_0}{E}$, that, as is known, it contradicts experiment. The second contradiction to the theory of heredity is developed during an abrupt change in the load: as a result of nonlinearity $\varphi(\epsilon)$ an increase in the deformation during an instantaneous change in the load is nonlinear connected with an increase in the load, which contradicts experiment.

Combined theories.

As already was noted, only the theory of heredity makes it possible to describe reverse creep; however, the conclusion of this theory of full/total/complete reversibility creep strain contradicts all known experiments in the investigation of creep of metals. In connection with this in recent years, were advanced the combined theories, making it possible to describe reversible component of

component/link.

Theories with the structural parameters.

As can be seen from that presented above, none of the theories of creep can describe entire diversity of the behavior of material over a wide range of temperatures. One of the reasons for this - impossibility to indicate from the positions of phenomenological representations the signs/criteria, which characterize the structural state of metal.

Formal of this it is possible to avoid, after introducing into the equation of creep certain number of structural parameters q_i [27]:

$$\dot{\epsilon}_n = f(\sigma, T, q_1, q_2, \dots, q_n). \quad (37)$$

Were proposed following theory creeps with one structural parameter [27, 34, 30].

Theory of strengthening, which considers temperature softening in the process of creep test [27].

After placing

$$dq = d\epsilon_n + cdt, \quad (38)$$

where c - coefficient, which characterizes the rate of softening

creep with the aid of the theory of heredity, and irreversible component - with the aid of the theory of strengthening [30, 31] and of aging [32].

The use of the combined theory in the formulation of G. I. Bryzgalin [31] for describing the behavior of material with varying stresses requires determining the characteristics of creep with constant stresses and the characteristics of reverse creep. The combined theory in the formulation of Ye. A. Zeyn [30] is instituted on the proposed by the author rheological model of creep, which consists of the component/link of Maxwell and certain number of Kelvin - Voigt's component/links (see Chapter I); Maxwell's component/link it simulates irreversible component of creep, the component/links of Kelvin - Voigt - reversible.

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The nucleus of aftereffect, according to this model, takes the form

$$K(\tau - \tau^*) = \sum_{i=1}^n \frac{1}{\eta_i} \exp \left[\frac{E_i(\tau - \tau^*)}{\eta_i} \right], \quad (36)$$

where E_i and η_i - stiffness coefficients and ductility/toughness/viscosity of Kelvin - Voigt's i -th

where σ_0 - initial stress; k_1 - factor of the defectiveness of material, depending on testing temperature, we will obtain the following modification of the law of hardening in equation (41):

$$\dot{\varepsilon}_n \varepsilon_n^\lambda = K \exp \left\{ \frac{\sigma}{A} (1 + k_1 \varepsilon_n) \right\}. \quad (44)$$

Theory of flow and strengthening, which consider softening or strengthening with of creeps, caused by the instantaneous plastic deformation, accumulated in the process of testing. For describing of strengthening or softening under conditions of creep of the heat-resistant alloys, which undergo in the process of testing the effect of instantaneous plastic strain ($\sigma > \sigma_y$), it was suggested to utilize in the equations of creep as the structural parameter an amount of accumulated instantaneous plastic deformation (ε_{nn}^0).

For the case of the similarity of curves of creep with different degree of work hardening at the stage of transient creep, certain function S from the structural parameter can be introduced as factor to the first member of expression (21b).

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On the basis of processing experimental data on creep with

constant stresses [34] is recommended the following expression for S:

$$S = 1 + h [\varepsilon_{\text{m}}^0 - f(\sigma)]^r, \quad (45)$$

where $f(\sigma)$ - the amount of plastic deformation, which corresponds to stress σ , according to stress-strain curve; h and r - constant.

In the case of strengthening $h < 0$, while in the case of softening $h > 0$. Real/actually, after accepting for describing the curves of instantaneous deformation the equation of the form

$$\varepsilon = \frac{\sigma}{E} + \alpha \left(\frac{\sigma}{\sigma_y} \right)^q, \quad (46)$$

where α and q - constant, σ_y - elastic limit, we will obtain

$$S = 1 + h \left[\alpha \left(\frac{\sigma_{\text{max}}}{\sigma_y} \right)^q - f(\sigma) \right]^r, \quad (47)$$

where σ_{max} - the stress, which caused the formation of plastic deformation ε_{m}^0 .

For $\sigma = \sigma_{\text{max}}$ $S \equiv 1$. Hence $f(\sigma) = \alpha \left(\frac{\sigma}{\sigma_y} \right)^q$. It was shown, that the expression for S retains its form for the different values of stress and does not depend on accumulated creep strain.

One should, however, note, that expressions (45) and (47) are valid only for the limited values ε_{m}^0 , which do not exceed 3-5%.

The proposed expression for functioning the structural parameter

$(c < 0)$, and after making an assumption about the fact that $c = -\mu q$, we will obtain

$$dq = d\varepsilon_n - \mu q d\tau. \quad (39)$$

With

$$\begin{aligned} \sigma = 0, \quad \varepsilon_n = 0, \quad dq = -\mu q d\tau \\ q = q_1 \exp(-\mu \tau), \end{aligned} \quad (40)$$

where τ is counted off from the torque/moment of unloading (when $\varepsilon_n = \varepsilon_{n1}$). It is hence obvious that $1/\mu$ can be considered as the characteristic time of softening. If this time is sufficiently great, then $q \approx \varepsilon_n$.

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After accepting equation (39) and following analytical expression for the law of hardening:

$$\dot{\varepsilon}_n \dot{\varepsilon}_n^\lambda = K \exp(\sigma/A), \quad (41)$$

we will obtain the equation, which makes it possible to describe creep of the softened material:

$$\mu q^{\lambda+1} + \dot{q}q^\lambda = K \exp(\sigma/A). \quad (42)$$

Theory of strengthening, which considers defectiveness in the process of testing [30]. After accepting the linear dependence of the actual stress in specimen/sample from the amount of accumulated creep strain

$$\sigma = \sigma_0(1 + k_1 \varepsilon_n), \quad (43)$$

retains its form, also, for a creep rate.

Thus, the equation of the theory of flow with the structural parameter can be obtained as a result of the following modification of equation (27a) :

$$\frac{de_n}{d\tau} = Q_1(\sigma) \frac{\partial \Psi(\sigma, \tau)}{\partial \tau} S + Q_2(\sigma). \quad (48)$$

For using formula (48) within the framework of the theory of strengthening from it it is necessary to eliminate time by the substitution of the corresponding values from the equation

$$e_n = Q_1(\sigma) \Psi S + Q_2(\sigma) \tau. \quad (48a)$$

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2. On communication/connection of relaxation of stresses and of creep.

Theories described above of creep allow for the basis of experimental data on creep with constant stresses to design relaxation curves. Such calculations can be performed graphically and analytically.

Subsequently will be examined the conditions of ideal relaxation, when during loading prior to the relaxation test of creep

it is not observed [39].

The equation of pure relaxation can be obtained from the differential equation

$$\frac{d\sigma}{dt} = -E\dot{\epsilon}_n. \quad (49)$$

Assuming that $\dot{\epsilon}_n$ it does not depend on time [stationary creep $\dot{\epsilon}_n = Q_2(\sigma)$], and, after integrating expression (49) under initial conditions $t=0, \sigma=\sigma_0$, we will obtain

$$t = -\frac{1}{E} \int_{\sigma_0}^{\sigma} \frac{d\sigma}{Q_2(\sigma)}. \quad (50)$$

Let us take the form of the dependences $\dot{\epsilon}_n$ on the stress in the form of the formulas, proposed by Norton, Iyudvik and Nadai, respectively

$$\dot{\epsilon}_n = A\sigma^l, \quad (51a)$$

$$\dot{\epsilon}_n = Be^{k\sigma}, \quad (51b)$$

$$\dot{\epsilon}_n = C \operatorname{sh}(m_1 \sigma), \quad (51c)$$

where A, B, C, l, k, m_1 - constant.

Then from relationship/ratio (50) we obtain formulas for determining the relaxation time respectively for equations (51a)-(51c) [50]:

$$\tau = \frac{1}{(l-1)AE} \left(\frac{1}{\sigma^{l-1}} - \frac{1}{\sigma_0^{l-1}} \right), \quad (52)$$

$$\tau = \frac{1}{kBE} (e^{-k\sigma} - e^{-k\sigma_0}), \quad (53)$$

$$\tau = \frac{1}{m_1 CE} \lg \frac{\operatorname{th} \frac{m_1 \sigma_0}{2}}{\operatorname{th} \frac{m_1 \sigma}{2}}. \quad (54)$$

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At the high values of time τ and the sufficiently high temperatures when remaining stress (σ) is considerably lower than the initial (σ_0), relationship/ratios (52)-(54) are simplified:

$$\tau = \frac{1}{(l-1)AE\sigma^{l-1}}, \quad (52a)$$

$$\tau = \frac{1}{kBE} e^{-k\sigma}, \quad (53a)$$

$$\tau = -\frac{1}{m_1 CE} \lg \left[\operatorname{th} \frac{m_1 \sigma}{2} \right]. \quad (54a)$$

Formulas (52) and (52a) are valid with $l \neq 1$. With $l=1$ the solution of equation (49) is converted into the known equation of Maxwell:

$$\frac{d\sigma}{d\tau} = -k\sigma, \quad (55)$$

the having solution

$$\sigma = \sigma_0 \exp(-k\tau). \quad (56)$$

According to equation (52a), relaxation curve can be represented

in the form of straight line in the dual logarithmic coordinates $\lg \sigma - \lg \tau$. In accordance with equations (53a) and (54a) during some limitations relative to constants m_1 and C relaxation curve can be represented in the form of straight line with semilogarithmic coordinates $\sigma - \lg \tau$. And finally according to equation (56), must be observed linear dependence in coordinates $\lg \sigma - \tau$.

However, the absence of the unsteady stage of creep is observed only under conditions of rapid creep and only at very high temperatures.

The expressions, which describe relaxation processes, were refined by a number of the authors. Formula (56) was modified by B. M. Rovinskiy and to V. G. Lyuttsa [40] by the introduction of exponent p , named plasticity index or index of the relaxation compliance/pliability:

$$\sigma = \sigma_0 \exp [-(k\tau)^p]. \quad (57)$$

The comparison of test results with the values $\sigma(\tau)$, obtained by calculation according to formula (57), it is shown, that p varies from 0 to 1 depending on the concentration of alloying ingredients, value of residual deformation, temperature, hardness [41, s. 271].

Another attempt to refine the formula, which describes relaxation curves, was made by Baushis [41, p. 33]. After presenting formula (52) in the form

$$\sigma = \sigma_0 [1 + (l-1)AE\tau\sigma_0^{l-1}]^{\frac{1}{l-1}} \quad (58)$$

and after replacing AE with the proposed [19] expression

$$AE = \frac{a}{b+\tau} \left(c + \frac{\tau}{1+\lg\tau} \right), \quad (59)$$

was obtained the following empirical dependence:

$$\sigma = \sigma_0 \left[1 + (l-1) \frac{a\tau}{b+\tau} \left(c + \frac{\tau}{\lg\tau} \right) \sigma_0^{l-1} \right]^{\frac{1}{l-1}}, \quad (60)$$

where a, b, c and l - constants.

For the determination of the equations of relaxation in general form, it is necessary to accept the other one or hypothesis of creep.

From aforesaid are visible the vital differences for resistance of relaxation and creep under conditions of prolonged service lives. Creep strain, accumulated in the service life of material, as a rule, in essence is determined by the strain, accumulated at the steady stage, since creep at the unsteady stage is comparatively small. Relaxation resistance is determined to a considerable extent by creep rate at the unsteady stage.

Most characteristically this is developed on titanium alloys

whose steady creep rate in the range of the temperatures of strain aging (300-350°C) is close to zero.

In the investigated in work [42] alloys of brands AT-3 and VT-8, is revealed/detected the limit of relaxation σ_r , characterized by the point of intersection of straight lines $\Delta\sigma - \sigma_0/\sigma_{0,2}^T$ appropriate $\tau=\text{const}$, on axle/axis $\sigma_0/\sigma_{0,2}^T$.

FOOTNOTE 1. $\sigma_{0,2}^T$ - yield point at temperature T. ENDFOOTNOTE.

With an increase in the temperature, ratio/relation $\sigma_r/\sigma_{0,2}^T$ decreased at 300-350°C. However, at these temperatures value $\Delta\sigma$ proved to be considerably less than at 20 and 450°C.

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In connection with that presented when development of relaxation-resistant materials and selecting of the conditions/mode of their heat treatment, considerable attention should give to an increase in the creep strength not only in that being steady, but also at the unsteady stage.

Simple is the graphic method of the plotting of curves of relaxation in accordance with the theory of aging on the basis of

isochronal curves (Fig. 9). Real/actually, after dropping perpendicular to the axle/axis of abscissas from the point of the curve of instantaneous deformation ($\tau=0$), that corresponds to the torque/moment of loading, we will obtain at points of intersection with isochronal curves $\tau=\tau_1$, $\tau=\tau_2$ and so forth the appropriate values σ_τ .

According to the theory of flow, the graphic plotting of curves of relaxation on the basis of known curves of creep at k values σ can be produced as follows [43].

After replacing in equation (49) differentials with finite differences, we will obtain

$$\frac{\Delta\sigma}{\Delta\tau} = -E\varepsilon_n. \quad (61)$$

The interval of integration let us break into sections

$\Delta\sigma_i = \sigma_{i+1} - \sigma_i$ ($i=0, 1, 2, \dots, k-2$). For an i -th interval we have the difference relationship/ratio

$$\Delta\tau_i = -\frac{\Delta\sigma_i}{E} \cdot \frac{1}{\dot{\varepsilon}_n(\sigma_i, \tau_i)}, \quad (62)$$

where value $\dot{\varepsilon}_n(\sigma_i, \tau_i)$ - rate of change to curve of creep when $\sigma=\sigma_i$, $\tau=\tau_i$. Consecutively transfer/converting from one interval $\Delta\sigma_i$ to another, it is possible thus to construct entire curve of relaxation.

In work [43] is proposed the method of graphic interpolation,

which makes it possible to manufacture the constructions indicated with the limited number of experimental curves of creep.

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After changing over the curves of creep and the curves dependences of the deformation rate on time into curves $\dot{\varepsilon}_n = f(\varepsilon_n)$ for different stresses and accepting time interval by equal to $\Delta\tau$, we consecutively calculate values

$$\Delta\sigma_i = E\Delta\varepsilon_{n_i} = E\varepsilon_{n_i}\Delta\tau, \quad (63)$$

where value ε_{n_i} is determined for a curve, that corresponds to the previous value σ , and it answers accumulated creep strain $\varepsilon_{n_{i-1}} = \sum_{k=i}^{i-1} \varepsilon_{n_k}$.

Let us examine the analytical methods of the plotting of curves of relaxation in the presence of elastic component/link with compliance/pliability e .

According to the theory of aging from the equation of the relaxation

$$\varepsilon_n + \frac{\sigma}{E}(1+cE) + \varepsilon_m + \varepsilon_c = \varepsilon_0 = \frac{\sigma_0}{E}(1+cE) + \varepsilon_m, \quad (64)$$

where $c = \frac{eF}{l_0}$; F - area of specimen/sample; l_0 - its length, we have

$$\frac{\sigma_0 - \sigma}{E}(1+cE) = \varepsilon_n(\sigma, \tau) + \varepsilon_c(\sigma, \tau) = Q_1(\sigma)\Psi + Q_2(\sigma)\tau. \quad (64a)$$

After accepting the similarity of curves of creep and the power

dependency of creep strain on the stress

$$\dot{\epsilon}_n(\sigma, \tau) = \Omega_1(\tau) \sigma^m, \quad (65)$$

we will obtain

$$\frac{E\Omega_1(\tau)}{1+cE} \sigma_0^{m-1} = \frac{1-\rho}{\rho^m}, \quad (66)$$

where $\rho = \sigma/\sigma_0$.

After differentiation of expression (64) we will obtain equation for determining stress relaxation from the theory of the flow:

$$\dot{\epsilon}_n = - \frac{d\sigma}{d\tau} \frac{1+cE}{E}. \quad (67)$$

It differentiated (65) and after substituting into formula (67), after integration we will obtain

$$\rho = \left(1 + \frac{(m-1)E\Omega_1(\tau)}{1+cE} \sigma_0^{m-1} \right)^{1-m}. \quad (68)$$

From expression (68) it follows that with an increase in the initial stress and the decrease of compliance/pliability descends the value ρ . Between the expressions, which describe relaxation on the hypothesis of flow and the hypothesis of constant velocity, there is specific communication/connection.

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After accepting the expression

$$\dot{\epsilon}_n = B(\tau) \varphi(\sigma), \quad (69)$$

from the equation of the relaxation

$$\frac{1}{E} \cdot \frac{d\sigma}{d\tau} + B(\tau) \varphi(\sigma) = 0, \quad (70)$$

we have

$$\int_0^{\tau} B(\tau) d\tau = - \frac{1}{E} \int_{\sigma_0}^{\sigma} \frac{d\sigma}{\varphi(\sigma)}.$$

With $\tau > \tau^*$, where τ^* - time of the onset of the steady stage of creep,

$$\int_0^{\tau} B(\tau) d\tau = \int_0^{\tau^*} B(\tau) d\tau + \int_{\tau^*}^{\tau} B(\tau) d\tau = B^* + B(\tau - \tau^*),$$

where B^* - constant of material.

Then

$$\tau + \tau_1 = - \frac{1}{E} \int_{\sigma_0}^{\sigma} \frac{d\sigma}{B\varphi(\sigma)}, \quad (71)$$

where

$$\tau_1 = \frac{B^* - B\tau^*}{B} > 0.$$

Hence

$$\tau = - \frac{1}{E} \int_{\sigma^*}^{\sigma} \frac{d\sigma}{B\varphi(\sigma)}, \quad (72)$$

where $\sigma^* < \sigma_0$.

Since $B\phi(\sigma)$ - the rate of steady-state creep, comparing formulas (50) and (72), we see that with $\tau > \tau^*$ the relaxation over the theory of flow occurs/flow/lasts just as relaxation over the theory of steady creep, but with the reduced initial stress.

According to the theory of strengthening, the process of relaxation is described as follows.

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After substituting in (67) expression (28), after expressing in it ε_{tt} from the condition of relaxation (64):

$$\varepsilon_{tt} = \varepsilon_0 - \varepsilon_{nn} - \frac{\sigma}{E}(1 + cE), \quad (73)$$

we will obtain differential equation, which describes the process of relaxation according to the theory of the strengthening:

$$\frac{d\sigma}{d\tau} = -\frac{E}{1+cE} f \left\{ \left[\varepsilon_0 - \varepsilon_{nn} - \frac{\sigma}{E}(1 + cE) \right], \sigma \right\}. \quad (74)$$

As an example let us examine the equation of relaxation for the law of hardening in the form of equation (41). Substituting in expression (41) value ε_{tt} from condition (67) and ε_{tt} from (74) and integrating, we will obtain

$$\tau = \frac{1+cE}{E} \int_{\sigma}^{\sigma_0} \left[\varepsilon_0 - \varepsilon_{nn} - \frac{\sigma}{E}(1 + cE) \right]^{\lambda} e^{-\frac{\sigma}{A}} d\sigma \quad (75)$$

or

$$\tau = \left(\frac{A}{E} \right)^{1+\lambda} \frac{1+cE}{E} \exp \left[-\frac{E(\varepsilon_0 - \varepsilon_{nn})}{A} \right] \int_{x_0}^x x^{\lambda} e^x dx, \quad (75a)$$

where

$$x = \frac{E(\varepsilon_0 - \varepsilon_{in}) - \sigma(1 + cE)}{A}.$$

The equation of relaxation for the theory of heredity can be obtained from expression (29), solving the integral equation of Volterra relative to stress. Then we have

$$\sigma(\tau) = \varphi(\varepsilon) - \int_0^\tau \Gamma(\tau - \tau^*) \varphi(\tau^*) d\tau^*, \quad (76)$$

where $G(\tau - \tau^*)$ - the resolvent of the nucleus of aftereffect $K(\tau - \tau^*)$.

After assuming $\varepsilon = \varepsilon_0 = \text{const}$, we will obtain

$$\sigma(\tau) = \varphi(\varepsilon_0) \left[1 - \int_0^\tau \Gamma(\tau - \tau^*) d\tau^* \right]. \quad (77)$$

Since $\varphi(\varepsilon_0) = \sigma_0$, the equation of relaxation for the theory of heredity takes the form

$$\sigma = \sigma_0 [1 - R(\tau)], \quad (78)$$

where

$$R(\tau) = \int_0^\tau \Gamma(\tau - \tau^*) d\tau^*. \quad (79)$$

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The examination of expression (78) shows that relaxation curves are similar.

The equation of relaxation within the framework of combined theory [8] for the simplest case of model with one component/link of Kelvin-Voigt find following form.

It differentiated equation of state

$$\epsilon(\tau) = \frac{\sigma(\tau)}{E_0} + \epsilon_n + \int_0^{\tau} \frac{1}{\eta_1} \exp\left[\frac{E_1(\tau - \tau^*)}{\eta_1}\right] \sigma(\tau^*) d\tau^*, \quad (80)$$

we will obtain

$$\frac{d}{d\tau} \left(\epsilon - \frac{\sigma}{E_p} - \epsilon_n \right) + \frac{E_1}{\eta_1} \left(\epsilon - \frac{\sigma}{E_p} - \epsilon_n \right) + \frac{\sigma}{E_1} = 0, \quad (81)$$

where $E_p = \frac{E_0 \cdot E_1}{E_0 + E_1}$ — the completely relaxed modulus of elasticity.

Disregarding some terms and after eliminating from examination comparatively short relaxation times, it has

$$\tau = -\frac{1}{E_p} \int_{\sigma_0}^{\sigma_t} \frac{d\sigma}{\dot{\epsilon}_n(\sigma, \epsilon_n, \tau)}, \quad (82)$$

where $\sigma_0^* = \frac{E_p}{E_0} \sigma_0$.

Can be placed the inverse problem: construct in the curves of relaxation (pure/clean and with elastic component/link) curves of creep with constant stresses.

Thus, for instance, according to the theory of flow, creep strain determines as follows [32]. Let us accept

$$\dot{\epsilon}_n = B(\tau) \sigma^m, \quad (83)$$

$$\dot{\epsilon}_n + \dot{\epsilon}_y = \dot{\epsilon}_0. \quad (84)$$

It differentiated expression (84) and integrating the obtained differential equation, we will obtain after some conversions the following expression, which describes the process of the relaxation:

$$\rho = \frac{\sigma}{\sigma_0} = \left[1 + (m-1) E \sigma_0^{m-1} \int_0^\tau B(\tau) d\tau \right]^{\frac{1}{1-m}}. \quad (85)$$

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Bearing in mind that $\sigma_0^m \int_0^\tau B(\tau) d\tau = \varepsilon_n(\tau)$ with $\sigma_0 = \text{const}$, and $\sigma_0/E = \varepsilon_0$, we will obtain the following equation of creep, which determines value $\varepsilon_n(\tau)$ through the characteristics of relaxation and constant m :

$$\varepsilon_n(\tau) = \frac{\varepsilon_0}{m-1} [\rho^{1-m} - 1]. \quad (86)$$

Expression (85) for experiments to the relaxation with elastic component/link with compliance/pliability $c = \frac{\varepsilon_0}{\sigma}$ takes the form

$$\rho = \left[1 + \frac{m-1}{cE+1} E \sigma_0^{m-1} \int_0^\tau B(\tau) d\tau \right]^{\frac{1}{1-m}}. \quad (87)$$

Knowing the compliance/pliability of elastic component/link and after conducting simultaneous experiments with $\sigma_0 = \text{const}$, under conditions of pure relaxation with elastic component/link, we will obtain from equation (87) expression for determining the constant m :

$$\left(\frac{\sigma}{\sigma_0} \right)^{1-m} - 1 = (cE + 1) \left[\left(\frac{\sigma_0}{\sigma} \right)^{1-m} - 1 \right], \quad (88)$$

where σ and σ_0 — end stress in experiments on pure relaxation and relaxation with elastic component/link respectively.

On the basis of the theory of aging curves of creep can be obtained from relaxation curves by sufficiently simple graphic constructions, which are reduced to the construction of the diagram of a deformation of the type, given to Fig. 9.

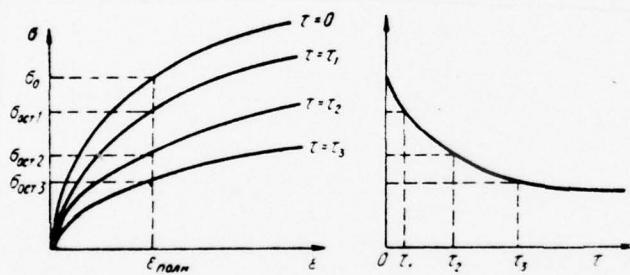


Fig. 9. Schematic of the plotting of curves of relaxation on the data of creep in accordance with the theory of aging.

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3. Experimental data.

One of they are first studies in which was conducted the comparison of experimental and calculated curves of relaxation, is Davis's work [44]. Established/installled satisfactory conformity of the curves of the relaxatior of copper with 20°C, obtained on base 0.1-1000 h.

The equation of the relaxation

$$\tau = -c \int_{\sigma_0}^{\sigma} \frac{(\sigma_0 - \sigma)^{p_1}}{\sigma^q} d\sigma \quad (89)$$

was obtained and the approximation of curves of creep in the form

$$\dot{\epsilon}_n = k_1 \sigma^{p_1+1} \tau^{\frac{1}{p_1+1}} \quad (90)$$

and of differential equation, corresponding to the hypothesis of the strengthening:

$$\dot{\epsilon}_n = k \frac{\sigma^q}{\dot{\epsilon}_n^{p_1}} \quad (91)$$

However, the results of the tests of copper with 165°C badly/poorly were described with the aid of formulas (89), (90). At elevated temperatures better/best conformaty give calculations according to formula [45]:

$$\tau = - \int_{\sigma_0}^{\sigma} \frac{1}{m(Ek)^{1/m}} \cdot \frac{(\sigma_0 - \sigma)^{\frac{1-m}{m}}}{(e^{\sigma/S} - 1)^{1/m}} d\sigma, \quad (92)$$

to the brought out on basis theory of strengthening and approximation of data according to creep in the form

$$\varepsilon_n = k (e^{\sigma/S} - 1) \tau^n. \quad (93)$$

Calculations according to the theory of the flow of distance understated, and on the hypothesis of aging the high values of the remaining stress (Fig. 10).

The calculations of the curves of the relaxation of steel 30KhMA at 500°C carried out in work [46] through the theory of strengthening. The duration of creep tests and relaxation comprised 100 h.

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The specimen/samples prior to testing were subjected annealing for 1 h at temperature of 600°C.

For Calculation was utilized the approximation of curves of

creep in the form of the formula, escape/ensuing from the law of hardening in the form of expression (41):

$$\dot{\epsilon}_n = \left(\frac{k}{T} \right)^m \left(\exp \left[\frac{\sigma m}{A} \right] \right) \tau^m, \quad (94)$$

where $m=1/(1+\lambda)$.

ta from formula (94) it follows that in the dual logarithmic coordinates of the dependence $\dot{\epsilon}_n$ on τ they are depicted as straight lines. However, it turned out that the coefficient of strengthening λ and constant A depend on stress.

Were calculated relaxation curves, according to expression (75a), for the constant average values $m=0.529$, $k=2.766 \cdot 10^{-10}$ 1/h, $A=29.4 \text{ MN/m}^2$ (2.94 kg/mm²) taking into account the linear dependence m and A on stress.

tab the comparison of calculated and experimental curves showed that communication/connection between creep and stress relaxation in steel 30KhMA at 500°C satisfactorily is described in accordance with the theory of strengthening. The accuracy/precision of the obtained on base 100 h results does not exceed the limits of the accuracy/precision of the approximating formulas, which were being applied during processing of experimental data.

Separate experiments to relaxation carried out also under conditions of previous creep (~0.25% after 25 h). The fact of the retarding/deceleration/delay of relaxation by previous creep is explained with the position of the theory of strengthening.

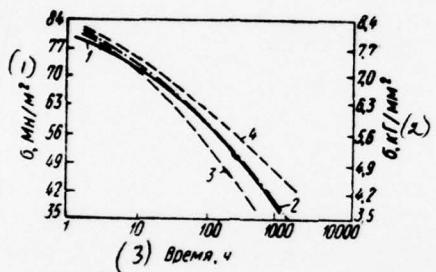


Fig. 10. The curves of the relaxation of copper with 165°C , $\sigma_0=94.5 \text{ MN/m}^2$ (9.45 kg/mm^2) [45]: 1 - experimental; 2 - according to the theory of strengthening; 3 - according to the theory of flow; 4 - according to the theory of aging.

Key: (1). MN/m^2 . (2). kg/mm^2 . (3). Time, h.

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Comparatively small preliminary short-term plastic deformations of steel 30KhMA did not lead to the same strengthened/hardened effect, as the strain of the same value, but accumulated in the process of

creep.

However, as it was shown by investigations of one of the authors, with an increase in preliminary plastic deformation (ϵ_{pl}^0) resistance of relaxation proved to be dependent on ϵ_{pl}^0 . As can be seen from Fig. 11, preliminary plastic deformation to 30% with a temperature of the subsequent relaxation test (700-800°C) led to the noticeable decrease of the values of the remaining stress of alloys on the nickel basis of brands KhN70VMYuT, KhN70VMFTYu, Kh75VMFYu. This is explained, obviously, by the decrease of the creep strength of the work-hardened material in comparison with initial.

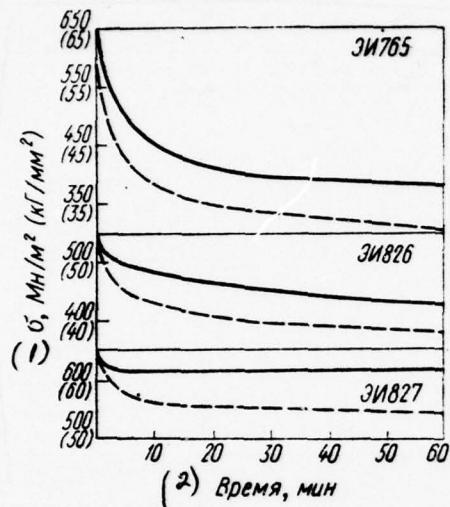


Fig. 11. Curves of the relaxation of alloys KhN70VMYuT at 750°C, KhN70VMFTYu at 750°C, KhN75VMFYu at 700°C in initial state (solid) and after preliminary elongation to 30% at the temperature of testing (dashed lines).

Key: (1). σ , MN/m² (kg/mm²). (2). Time, min.

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For testing of the validity of this assumption, the specimen/samples made of the alloys of brands KhN80TBYuA, KhN70VMYuT and KhNYuVMFTYu, deformed to $\varepsilon_{\text{rel}}^0 = 0 \div 4\%$ at 600-800°C, experience/tested on creep at temperatures [47] indicated. Creep tests carried out with stresses less even larger of elastic limit. It

was establish/installed, that:

- 1) the rate of rapid creep at the unstable stage increases with an increase in the degree of strain (Fig. 12); however, during 2-40% strain is observed a maximum and further increase $\varepsilon_{\text{un}}^0$ it causes a decrease in the velocity of creep.
- 2) creep rate at steady stage (v_{min}) does not virtually depend on the value of plastic defcrmaton $\varepsilon_{\text{un}}^0 = 0 \div 4\%$ (see Table 1).

The results of the conducted experiments were approximated by following analytical expressions [34]:

$$\dot{\varepsilon}_{\text{n}} = A\sigma^k [1 - \exp(-C\sigma^l\tau)] S + B\sigma^m\tau, \quad (96)$$

$$\dot{\varepsilon}_{\text{n}} = AC\sigma^{k+l} \exp(-C\sigma^l\tau) S + B\sigma^m, \quad (97)$$

where S - a function of the structural parameter of the amount of preliminary plastic defcrmaton. In connection with $\varepsilon_{\text{un}}^0 \leq 3 \div 5\%$ was suggested expression for S of form (45), which when $\sigma < \sigma_y$, and consequently, $f(\sigma) \sim 0$ takes the form

$$S = 1 + h(\varepsilon_{\text{un}})\tau. \quad (98)$$

As already mentioned, expressions (45) and (98) assume that the preliminary plastic defcrmaton has identical effect on the processes

of creep with different stresses, the limit inferior of elasticity.

With varying stresses S , we can be calculated with the aid of expression (47).

The analysis of expressions (96), (97), (47) makes it possible to assume that relaxation curves with different initial stresses, which exceed elastic limit ($\sigma_0 > \sigma_y$), can intersect between themselves, and also with relaxation curves when $\varepsilon_0 < \sigma_y$. Actually as showed experiments the short-term relaxation (Fig. 13), for the mentioned above alloys such intersection of relaxation curves was observed at the temperatures, for which with an increase in creep strain, the creep rate is decreased [$\lambda \neq 0$ in expression (41)].

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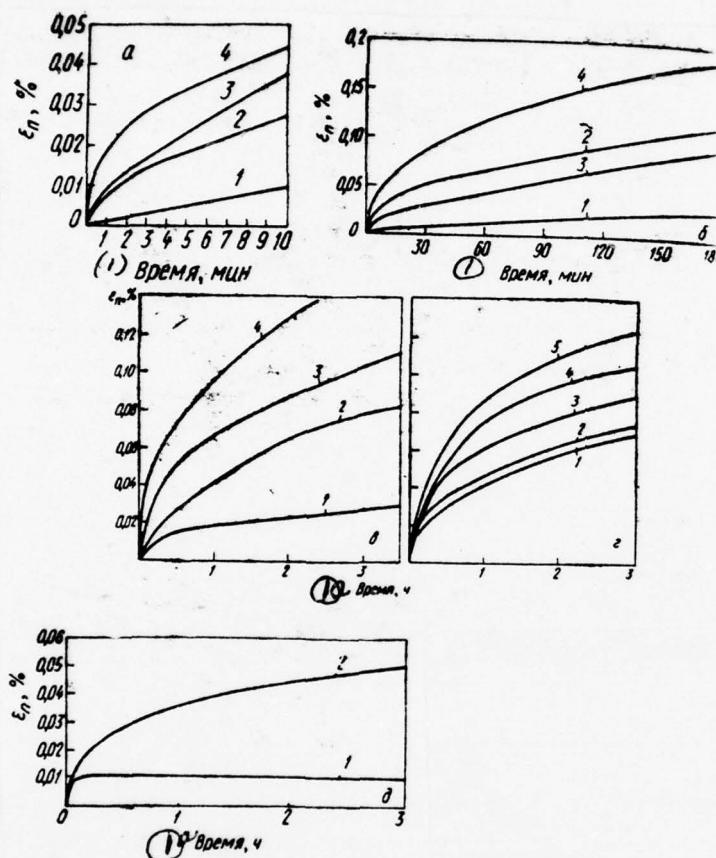


Fig. 12. Curves of short-term creep of nickel base alloys during different conditions/modes of preliminary plastic deformation.

Key: (1). Time, min. (1a). Time, h.

(1)	(2) Material	Tempera- ture, °C.	(3)		$\varepsilon_{\text{п.1}}$ %, соответствующая кривым				
			(4) MН/m ²	(5) kg/mm ²	1	2	3	4	5
a	XH80TVIA (ЭИ607A)	700	250	25	0	1,6	2,05	4,5	-
b*	XH70VMЮT (ЭИ765)	750	300	30	0	1,3	1,6	4,4	-
c*	XH70VMFTIO (ЭИ826)	700	500	50	0	0,93	2,71	3,86	-
d*	XH70VMFTIO (ЭИ826)	850	200	20	0	1,71	2,14	4,3	6,71
e*	XH73MBTIO (ЭИ698)	600	700	70	0	2,0	-	-	-

Key: (1). Fig. (2). Material. (3). Temperature, °C. (4). MN/m². (5). kg/mm². (6). — o/o, that corresponds to curves.

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At the same time at the high temperatures, of which the coefficient of strengthening $\lambda=0$, the curves of short-term relaxation for different σ_0 do not intersect and in the course of time (~10 min) coincide.

The applicability of different hypotheses of creep for describing the processes of the short-term relaxation of some heat-resistant alloys it was checked in the work of the authors L. V. Gertsov, A. G. Kostyuk and Yu. D. Martynov.

Steels 20Kh3MVF, 1Kh12VNMF, Kh15N35VT and alloys KhN80TVYuA, KhN70VMyuT, KhN70VMFTYu and KhN75VMFYu experience/tested for rapid

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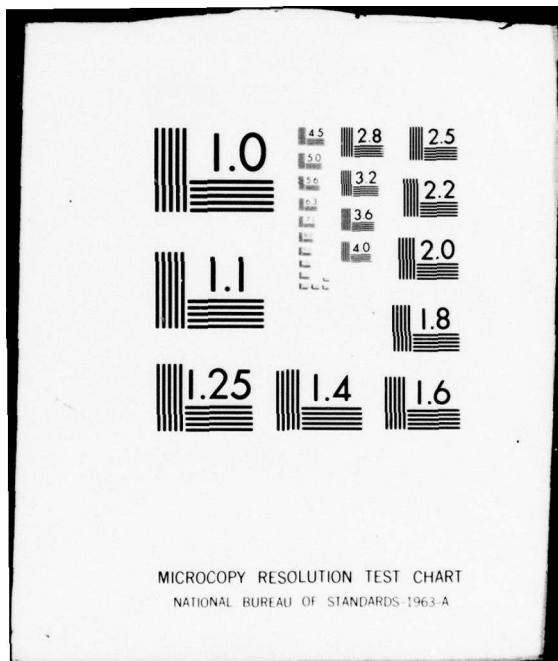
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creep and relaxation over a wide range to the temperature, the specimen/samples manufacturing from metal core melting and subjected to identical heat treatment.

Creep strain, accumulated with loading, did not exceed 0.005%, in connection with which of test conditions it is possible to consider as virtually corresponding to ideal relaxation [39].

Table 1. Dependence of the steady creep rate on the state of material.

(1) Материал	(2) Темпера-тура, °C	(3) Напряжение		$\dot{\epsilon}_{\text{пп}}^0, \%$	$\tau_{\text{min}} \text{ % } (4)$	
		(4) MN/m ²	(5) kg/mm ²			
110TБЮА (1607A)	650	350	35	0 1,14 1,93 3,93	$3,4 \cdot 10^{-2}$ $1,8 \cdot 10^{-2}$ $1,2 \cdot 10^{-2}$ $1,8 \cdot 10^{-2}$	
			250	0 1,6 2,05	$1,9 \cdot 10^{-2}$ $7,7 \cdot 10^{-2}$ $1,4 \cdot 10^{-2}$	
	700		250	0 1,3 1,6 4,4	$8,5 \cdot 10^{-3}$ $1,1 \cdot 10^{-2}$ $8,2 \cdot 10^{-3}$ $1,2 \cdot 10^{-2}$	
			300	0		
XH70ВМЮТ (1765)	750	300	300			

Key: (1). Material. (2). Temperature, °C. (3). Stress. (4). MN/m².
 (5). kg/mm². (6). h.

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Was utilized the approximation of curves of creep in the form of expressions (96) and (97), where S, according to equation (47), can vary within the range of 1 to $1+h(\dot{\epsilon}_{\text{пп}}^0)^t$.

Calculations were performed according to the theories of aging, flow, strengthening, and also the theories of flow and strengthening with the structural parameter, introduced into the equation of creep in the form of function S.

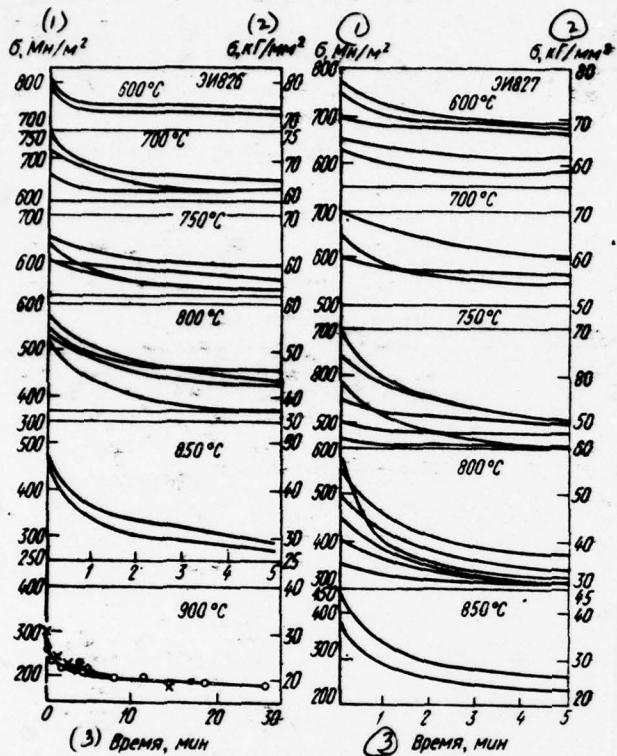


Fig. 13. Curves of the short-term relaxation of alloys on the nickel basis of π different temperatures and σ_0 [for 900°C $\sigma_0=320$, 370 and 400 MN/m^2 (32, 37 and 40 kg/mm^2)].

Key: (1). MN/m^2 . (2). kg/mm^2 . (3). Time, min.

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Utilizing equation (49), we will obtain the following expression for relaxation curves according to the theory of the flow:

$$\frac{d\sigma}{CA\sigma^{k+l}\exp(-C\sigma^l\tau)+B\sigma^m} = -Ed\tau \quad (99)$$

or in the finite differences

$$\Delta\sigma = -E [CA\sigma^{k+l}e^{-C\sigma^l\tau} + B\sigma^m] \Delta\tau. \quad (100)$$

Use of a hypothesis of flow with the structural parameter gives the expression

$$\Delta\sigma = -E [CA\sigma^{k+l}e^{-C\sigma^l\tau} S + B\sigma^m] \Delta\tau. \quad (101)$$

Calculations according to the theory of flow carried out with the aid of ETsVM "Minsk-22" and BESEM-2, moreover for by calculation according to expression (101) algcrithm was comprised in language ALGOL-60 (see appendix at the end of the book). Was used a variable step/pitch of integration $\Delta\tau$ in accordance with variable speed of the process of relaxation. Within step/pitch the calculations conducted by the method of the iterations (assigned/prescribed accuracy/precision was received as the equal tc 0.5c/o) and as the method of Runge-Kutta.

Calculations according to the theory of strengthening carried out by Davenport's method [28] with use instead of the network of experimental curved analytical dependences (96), (97). Thus, instead cf the continuous process of relaxation was calculated creep with the gradually changing stresses. The value of step/pitch on time was accepted as the equal tc 3 s. Calculations conducted with the aid of ETsVM "Minsk-22".

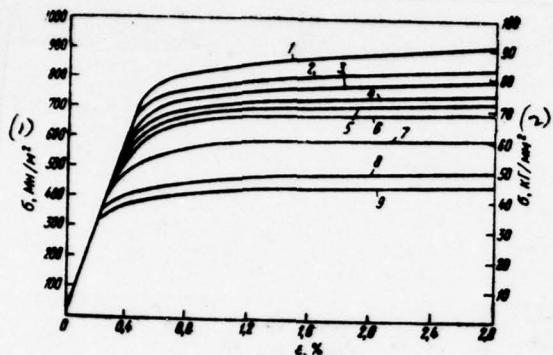
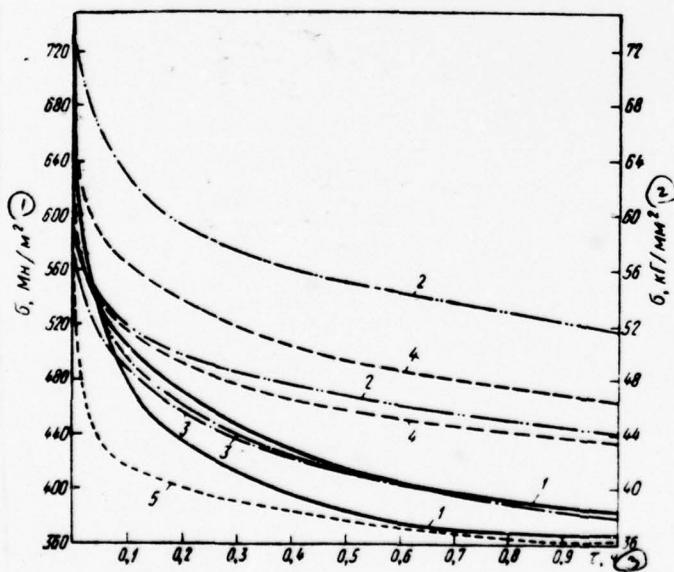
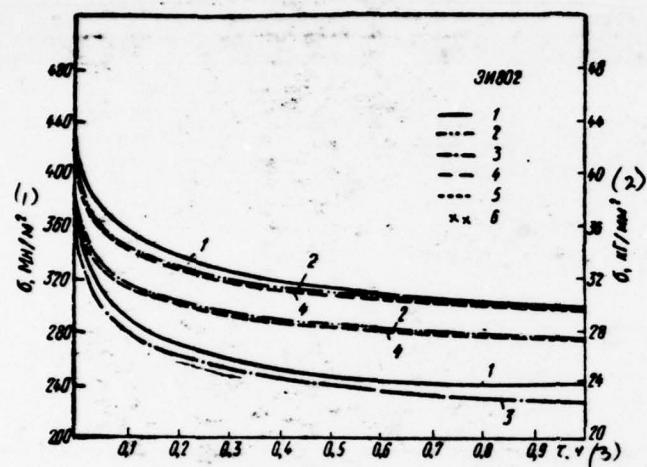


Fig. 14. The curved deflections of alloy KhN70VMuT at 700°C: 1 - instantaneous loading; 2 - 15 s; 3 - 15 min; 4 - 30 min; 5 - 1 h; 6 - 2 h; 7 - 10 h; 8 - 50 h; 9 - 10 h.

Key: (1) . MN/m². (2) . kg/mm².

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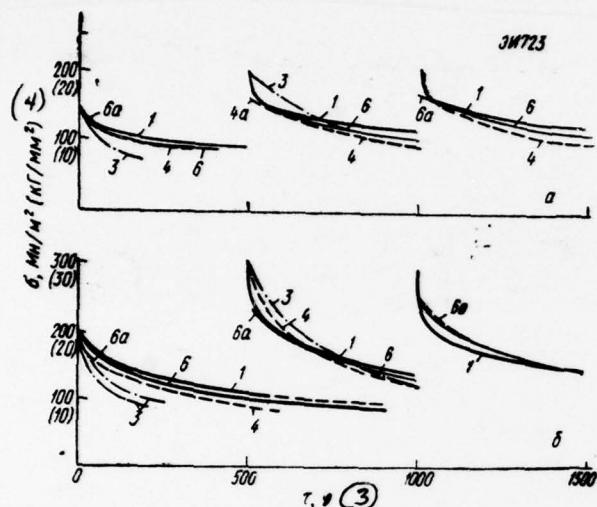


Fig. 15. The curves of the relaxation of steels 1Kh12VNMF and 25Kh2M1F and of alloy KhN70VMYut at different temperatures and with initial stresses: 1 - experimental curves; 2 - calculated by theory aging; 3 - according to the theory of flow; 4 - according to the theory of strengthening; 5 - according to the theory of flow with the structural parameter; 6 - according to the combined theory.

Key: (1). Alloy. (2). σ_0 , MN/m². (3). t , h. (4). σ , MN/m², (kg/mm²).

(1) Сплав	(2) σ_0 , MN/m ² (kg/mm ²)	(3) Номер кривой или рис. 15	(4) По данным
1Х12ВНМФ (ЭИ802)	550 400 (40)	1 2	(5) Л. Б. Гетсова
ХН70ВМЮТ (ЭИ765)	750 (75) 600 (10)	1 2	
25Х2М1Ф (ЭИ723)	200 (20) 300 (30)	а б	(6) Е. А. Хейн (30)

Key: (1). Alloy. (2). σ_0 , MN/m² (kg/mm²). (3). Number of curve or Fig. 15. (4). On data. (5). L. B. Getsova. (6). Ye. A. Heyn (30).

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The curves of temporary relaxation according to the hypothesis of aging were determined graphically by the isochronous creep curves (Fig. 14).

Calculated and experimental relaxation curves were compared separately for the initial stresses $\sigma_0 > \sigma_y$ and $\sigma_0 < \sigma_y$.

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As can be seen from those given in Table 2 and to Fig. 15 curved short-term relaxation, and also cumulative diagrams, constructed for the basis of 75 tests of seven different alloys at different temperatures (Fig. 16), best conformity with experiment detect the curves, designed by the theory of strengthening, especially for $\sigma_0 < \sigma_y$.

The results of calculations according to the hypothesis of flow give decreased values σ_t , and according to the theory of aging, - those overstated. However, for the initial stresses, which considerably exceed elastic limit when plastic deformation with loading exceeded 10%, experimental curves proved to be those below calculated by the theory of flow.

The observed intersection of relaxation curves when $\sigma_0 > \sigma_y$ was obtained only by calculations according to the theory of flow with the structural parameter.

Table 3 gives corrected values of the constants of expression (47), obtained from the diagrams of deformation and creep tests.

To Fig. 15, are given the results of calculations according to the theory of flow with the structural parameter and their comparison with experiment.

From Fig. 15, it is evident that the use of theory with the structural parameter makes it possible with a sufficient degree of accuracy to calculate curved short-term relaxation for $\sigma_0 > \sigma_y$ on the basis of the results of creep tests with constant stresses.

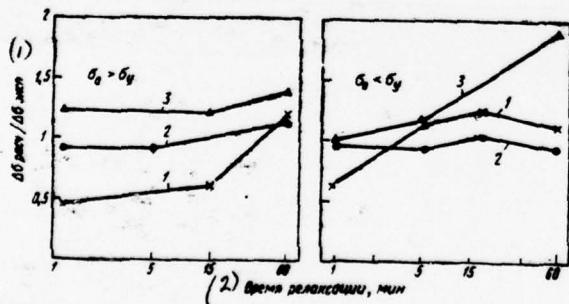


Fig. 16. The dependences between the ratio/relations of calculated and experimental values $\Delta\sigma = \sigma_0 - \sigma$ from relaxation time: 1 - according to the theory of aging; 2 - strengthening; 3 - flow (line are carried out through the points, which correspond to mean arithmetic values $\Delta\sigma_{\text{parc}} / \Delta\sigma_{\text{exp}}$.)

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Table 2. Comparison of experimental and computed values of the remaining stress for different alloys.

(1) Сталь или сплав	<i>t</i> , °C	σ_y	σ_0	(2) $\sigma_{\text{ост}} \text{ через } t=1 \text{ ч. МН/м}^2 (\text{кг}/\text{мм}^2)$, по различным гипотезам			
		(3) МН/м ² ($\text{кг}/\text{мм}^2$)		(4) старения	(5) упрочнения	(6) течения	(7) экспериментальные данные
20Х3МВФ (ЭИ415)	550	500(50) 500(50) 450(45) 400(40)	550(55) 350(35) 325(32,5) 300(30)	385(38,5) 336(33,6) 326(32,6) —	345(34,5) 281(28,1) 281(28,1) —	281(28,1) 281(28,1) 280(28) —	369(36,9) 331(33,1) 330(33) 296(29,6)
Х12ВНМФ (ЭИ802)	500	500(50) 400(40) 350(35)	450(45) 325(32,5) 290(29)	350(35) —	—	—	346(34,6) 292(29,2) 299(29,9)
	650	460(46) 450(45) 400(40) 350(35) 300(30)	500(50) — 295,5(29,55) 280(28) 275(27,5)	291(29,1) 278(27,8) 267(26,7) — —	291(29,1) 278(27,8) 267(26,7) — —	220(22) 220(22) 219(21,9) — —	292(29,2) 279(27,9) 237(23,7) 230(23) 226(22,6)
Х15Н35ВТ (ЭИ612)	650	395(39,5)	500(50) 450(45) 400(40)	405(40,5) 325(32,5) 320(32)	— 290(29) 290(29)	— 290(29) 290(29)	236(23,6) 270(27) 300(30)
ХН80ТВЮА (ЭИ607А)	700	350(35)	400(40) 350(35) 300(30)	375(37,5) 310(31) 290(29)	313(31,3) 288(28,8) 262(26,2)	287(28,7) 271(27,1) 249(24,9)	290(29) — —
ХН75ВМФЮ (ЭИ827)	600	610(61)	820(82) 800(80) 770(77) 750(75)	790(79) — — 742(74,2)	734(73,4) 724(72,4) 710(71) 699(69,9)	703(70,3) 699(69,9) 691(69,1) 684(68,4)	665(66,5) 689(68,9) 678(67,8) 739(73,9)
	700	600(60)	750(75) 720(72) 700(70) 690(69) 660(66)	638(63,8) — — — 608(60,8)	635(63,5) 626(62,6) 620(62) 616(61,6) 600(60)	588(58,8) 587(58,7) 585(58,5) 584(58,4) 577(57,7)	600(60) 545(54,5) 535(53,5) 660(66) 625(62,5)
	750	620(62)	650(65) 630(63)	600(60) 570(57)	517(51,7) 508(50,8)	460(46) 457(45,7)	512(51,2) 490(49)
	800	450(45)	570(57) 530(53) 500(50)	380(38) 360(36) 350(35)	350(35) 344(34,4) 339(33,9)	275(27,5) 275(27,5) 275(27,5)	368(36,8) 368(36,8) 330(33)
	850	370(37)	500(50) 450(45)	350(35) 310(31)	319(31,9) 274(27,4)	203(20,3) 203(20,3)	245(24,5) 245(24,5)

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Continuation Table 2.

ХН70ВМФЮТ (ЭИ765)	650	720(72)	820(82) 800(80) 750(75) 700(70)	770(77) 760(76) 725(72,5) —	690(69) 685(68,5) 568(56,8) 647(64,7)	639(63,9) 639(63,9) 635(63,5) 628(62,8)	615(61,5) 640(64) 675(67,5) 675(67,5)
	700	725(72,5)	800(80) 750(75) 700(70) 600(60)	656(65,6) 618(61,8) — —	620(62) 602(60,2) — —	544(54,4) 544(54,4) — —	507(50,7) 505(50,5) — —
	750	590(59)	750(75) 650(65) 600(60) 500(50)	516(51,6) 460(46) 440(44) 406(40,6)	463(46,3) 445(44,5) 432(43,2) 402(40,2)	378(37,8) 378(37,8) 377(37,7) 371(37,1)	365(36,5) 380(38) 380(38) 405(40,5)
ХН70ВМФЮ (ЭИ826)	600	610(61)	770(77) 750(75) 700(70) 650(65) 630(63)	750(75) 735(73,5) 690(69) 645(64,5) 625(62,5)	673(67,3) 666(66,6) 644(64,4) 616(61,6) 604(60,4)	635(63,5) 633(63,3) 624(62,4) 607(60,7) 598(59,8)	596(59,6) 604(60,4) 592(59,2) 584(58,4) 585(58,5)
ХН70ВМФТО (ЭИ826)	700	580(58)	700(70) 650(65) 600(60)	688(68,8) 635(63,5) 585(58,5)	613(61,3) 593(59,3) 569(56,9)	576(57,6) 572(57,2) 561(56,1)	517(51,7) 510(51) 590(59)
	750	570(57)	700(70) 650(65) 600(60) 550(55) 500(50) 470(47)	521(52,1) 490(49) 480(48) 456(45,6) 447(44,7) 429(42,9)	487(48,7) 478(47,8) 469(46,9) 455(45,5) 441(44,1) 428(42,8)	424(42,4) 424(42,4) 424(42,4) 423(42,3) 420(42) 416(41,6)	393(39,3) 378(37,8) 360(36) 425(42,5) 417(41,7) 445(44,5)
	800	510(51)	600(60) 550(55) 500(50) 450(45) 400(40) 350(35)	350(35) 320(32) — 290(29) 280(28) —	343(34,3) 335(33,5) 326(32,6) 315(31,5) 303(30,3) 287(28,7)	257(25,7) 267(26,7) 267(26,7) 267(26,7) 266(26,6) 263(26,3)	267(26,7) 293(29,3) 289(28,9) 249(24,9) 255(25,5) 270(27,0)
	850	570(57)	450(45) 400(40)	255(25,5) 240(24)	251(25,1) 239(23,9)	165(16,5) 165(16,5)	212(21,2) 213(21,3)

Key: (1). Steel or alloy. (2). for $\tau=1$ μ , MN/m² (kg/mm²), on different hypotheses. (3). MN/m² (kg/mm²). (4). aging. (5). strengthening. (6). flow. (7). experimental data.

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The comparison of the calculated and experimental curves of the relaxation of steel 25Kt2M1F (EI723) at 580°C under conditions of single and repeated loadings was undertaken in the investigation of Ye. A. Heyn [30]. Creep tests were conducted with constant stresses 100-400 MN/m² (10-40 kg/mm²) with the subsequent unloading and the determination of elastic after-effect.

Specimen/samples experience/tested for relaxation with initial stresses of 200, 300 and 400 MN/m² (20, 30 and 40 kg/mm²) with the repeated loadings (see Fig. 15, 1). Calculated curves of relaxation were constructed for the basis of data, designed by the theories of the flow (Fig. 15, 3) of strengthening (4) and of combined theory (6 and 6a).

When conducting of calculations according to the combined theory, they assumed that irreversible component, obtained by subtraction from creep strain of the strain of aftereffect, is subordinated to the laws governing the theory of strengthening, and

reversible component is approximated by Kelvin-Vcigt's two component/links with parameters η_1, E_1 and η_2, E_2 . It was establish/installed, that the last/latter assumption is in satisfactory agreement with experimental data.

expression (62), moreover

$$E_0 = \frac{E_1 E_2 E_0}{E_0 E_1 + E_0 E_2 + E_1 E_2}.$$

ENDFOOTNOTE.

The given in Fig. 15 comparison of the calculated and experimental curves of relaxation shows that their better/best conformity is provided during the use of the combined theory, worst - theory of flow.

Some disagreements, discovered at the initial stages of calculated and experimental curves with repeated loadings, Ye. A. Zheyn explains by the reduction of creep strength in the process of prolonged aging with 580°C.

Thus, survey/coverage of works conducted, in are which they were compared experimental and calculated curves of relaxation, it shows that with the stresses, the limit interior of elasticity, the theory of strengthening makes it possible to better describe this process of creep with variable stresses, such as it is stress relaxation. According to the combined theory of strengthening and plastic heredity, it is possible to obtain even better conformity with experiment.

Table 3. Constants for the calculation of value S according to formula (47).

(1) Material	Temperature °C.	(2)		h	α	q	r
		σ_n'	σ_y				
(3) MN/m^2 (kg/mm^2)							
ХН80ТВЮА (ЭИ607А)	650	350(35)	400(40)	101	0,00017	20,6	1,17
	700	250(25)	350(35)	185	0,000086	16,2	1,0
ХН70ВМЮТ (ЭИ765)	750	300(30)	590(59)	350	0,00033	15	1,2
ХН70ВМФЮ (ЭИ826)	700	500(50)	580(58)	10*	0,0002	19,4	3,54
	850	200(20)	280(28)	6,7	0,000054	9,1	0,6

' σ_n - the stresses, with which were determined constants h and r.

Key: (1). Material. (2) - Temperature, °C. (3) - MN/m^2 (kg/mm^2).

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On Fig. 15 in the form of curves 6 and 6a, are given respectively the results of precise and asymptotic solutions of equations, which correspond to the combined theory.

FOOTNOTE 1. Asymptotic solution for a model with Kelvin-Voigt's two component/links is described as for a model with one component/link,

Furthermore, at comparatively high temperatures of satisfactory agreement with experiment it is possible to achieve and calculation according to the theory of aging. If necessary calculation to determine the guaranteed limit of relaxation it is expedient to utilize theory of flow.

With the initial stresses which exceed elastic limit, relaxation curves can be calculated by the theory of flow with the structural parameter. At very high temperatures, and also for very high service lives relaxation can be designed with the aid of the formulas, instituted for the theory of the constant velocity of creep [$\dot{\epsilon}_n = f(\sigma)$].

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Chapter III.

METHODS OF STUDYING STRESS RELAXATION.

The process of relaxation consists of the decrease of elastic stress (deformations) and of accumulation of plastic deformation. However, unlike plastic deformation or creep plastic deformation during relaxation insignificant and in the volume of crystal body it is created because of very small shift/shears (fine/thin slip) along a large number of slip planes, distributed unevenly, which impedes their microscopic study. Therefore during the investigation of stress relaxation in essence, they are based on the determination of changes in the elastic deformation.

1. Relaxation with elongation and compression.

Are known different methods of studying stress relaxation under conditions of the unidirectional tension which differ, in particular, in the fact, is the unlading of specimen/sample in the process of tests necessary for the periodic measurement of residual stress or not.

As early as 1953 by B. M. Rovinskiy and to V. G. Lyuttsa was developed the method of tests, with which periodically is measured the cross section of the specimen/sample whose initial stretch deformation remains constant [48, 49].

Lateral deformation in tests at room temperature measures with the aid of special sensors [48], and at elevated temperatures - by a method of the reverse X-ray photographs of the transverse elastic deformation of grates [49].

Tests carry out as follows: the unstressed specimen/sample together with device for loading prior to testing establish/install in the X-ray camera/chamber for determining the period of lattice. Then specimen/sample they load and block with specimen/sample establish/install in the camera/chamber where periodically is measured the elastic deformation of lattice.

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In work [50] was proposed another X-ray method of studying stress relaxation. After the determination of the period of lattice in the initial unstressed state specimen/sample they rapidly dilate/extend to the assigned magnitude of plastic deformation, unload, and then in it periodically determine the period of lattice by precision X-ray photographing. This method is based on what in the deformed metallic specimen/sample during unloading appear the residual deformation of the lattices of opposite sign and compressive oriented microstress which relax of a similar to the stresses first kind.

For the investigation of the relaxation of tensile strength, are carried out the tests of stud pins and bolts in rings and of specimen/samples in special relaxation machines.

Test procedures in the rings of different construction/design are distinguished by degree of uniformity of heating ring and specimen/sample, by accuracy/precision of the measurement of residual deformations, by accuracy/precision of the maintenance of the

constant length of specimen/sample during testing, by productivity, utilized attachments for the creation of initial tension. The nonuniformity heating ring and bolt can cause the local overstresses of bolt. The insufficient difference in the section/cuts of ring and specimen/sample leads to a reduction in the rigidity of the rigidity of the stressed state.

Furthermore, almost for all methods of tests in rings is characteristic loading at room temperature and development of the processes of relaxation during the first stage at variable (increasing) temperature.

One of the first construction/designs of devices for the tests of stud pins and bolts for relaxation proposed by Mokbel' [51]. With each subsequent loading the stress in tested stud pin led to initial value. Thus, test conditions in these experiments differed from the conditions of pure relaxation. Metodika T. I. Volkov [70, p 170] is free from this deficiency and he makes it possible to carry out the measurement of the remaining stresses with an accuracy to $\sim 46 \text{ mN/mm}^2$ (0.4 kg/mm^2). The measurement of the length of specimen/sample conducts usually on general purpose microscope.

For the elongation of specimen/sample to the assigned magnitude of deformation, is utilized the special attachment (IR-4R), which is the combination of two open-end wrenches, connected spirally, on which is located the lever with handle. The complete revolution of handle creates tension 40 MN/m^2 (4 kg/mm^2). Heating device (IR-3) is calculated for a work in interval of $400\text{--}700^\circ\text{C}$. However, during the use of this method, are possible the overstresses of specimen/sample because of the uneven heating of specimen/sample and ring.

The more productive method of model tests of bolted joints is described by B. M. Rakhman [53], that proposed the construction/design of multiseater mandrel/mandrel. In this case the specimen/samples are warmed thoroughly somewhat faster than the ring, in connection with which it is eliminated the possibility of their overstresses.

For studying pure stress relaxation on testing machine, it is necessary to assign and to support the assigned/prescribed full/total/complete deformation of specimen/sample, to record/fix stress or change in the stresses in specimen/sample, to support with the specific accuracy/precision the assigned/prescribed temperature of specimen/sample.

The maintenance of the full/total/complete deformation of the

specimen/sample of constant presents considerable difficulties in connection with the adaptability of system and the difficulties of designing of the matching system of unloading [11, p 71]. Virtually the conditions of pure relaxation during tests in machines are not realized. For meeting for the requirements of machine indicated they have a loading device, a system for maintaining the deformation, a system for measuring the stresses and a thermostat (heating device) [60].

Basic machine parameters following:

1) the range of a change in the stresses and strains;

2) temperature range and the accuracy/precision of its maintenance;

3) the precision of measurements and maintenance of load;

4) the rate loading and unloading;

5) the evenness of load change;

6) reliability in continuous operation.

Are known different forms of the loading: with the aid of spring, sliding weight, load whose value is changed in the process of testing (spheres, water), of hydraulic press, etc. Each of the forms indicated possesses specific advantages and insufficiencies [54-58, 60].

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Thus, for instance, machines with the load, which are mixed on one lever, do not make it possible to carry out testing during the large initial plastic deformations of the specimen/sample, attached on the one hand. Machines with the load, which is decreased during testing, can manufacture only the unloading of specimen/sample. Loading by spring requires serious attention to the stability of the elastic properties of spring itself.

Besides the loading system, relaxation machines are distinguished by the systems, which ensure the maintenance of the assigned/prescribed deformation of specimen/sample. These systems, as a rule, consist of device, receiving and increasing deformation specimen/sample (enlarger of deformation); the devices, which develop/depletes electric pulses during the deviation of the size/dimensions of specimen/sample, and finally relay systems, governing the electric motor of the loading system.

Chevenard proposed to consider unit for measuring stress relaxation as the closed auto-oscillating looped system. In connection with this the requirements, presented on relaxation machines, are directed toward amplitude reduction of auto-oscillations, which is achieved by an increase in the rigidity of the parts of the enlarger of deformations, by an increase in the sensitivity of the system of impulser, by an increase in the rigidity of the loading system, by the decrease of the inertia of the driving/moving machine parts and by the decrease of friction in the articulation of the loading system. The amplitude of auto-oscillations affect such machine parameters how the rate of loading and unloading, set-up time of given speed of loading or unloading after the procedure by the loading system of the momentum/impulse/pulse of switching.

Table 4 gives fundamental performances for relaxation tests with elongation. A deficiency in some machines lies in the fact that in the process of testing is possible only the decrease of load; at the same time structural transformations and changes in the temperature during testing require its increase.

Table 4 shows that the described in the literature [54, 56-66]

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units are distinguished by the method of loading, by the accuracy/precision of the maintenance of the length of specimen/sample, with the maximum load, rate of loading and unloading, by rigidity¹.

FOOTNOTE¹. Majority of indicated devices are described in monograph [60]. ENDFOOTNOTE.

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Table 4. Devices for testing of spec. men/samples for the relaxation
of tensile strength.

(1) Тип установки	(2) Принцип действия	(3) Основные характеристики	(4) Источник
Barra . Bardgett	(5) Начальное напряжение создается затягом гайки. Напряжение определяется по деформации эталонного стержня, жесткость — податливостью стержня		[102]
Davis	То же (6)		[59]
Cran Co	(7) Напряжение создается пружиной, натяжение которой достигается завинчиванием гайки		[5]
Naday a. Boyd (Westinghaus General Electric)	(8) Машина компенсационного типа (при удлинении образца на 0,0002% замыкается контакт, который через реле приводит в действие двигатель, ослабляющий нагружающую пружину)		[61]
Рел-5 (VEB— Werkstoffprü- maschinen, ГДР, Лейпциг)	(9) Нагружение с помощью пружин. Изменение длины образца передается через кварцевые стержни на систему рычагов, регулирующей положение диафрагмы, в свою очередь влияющей на поток света, падающего на фотоэлемент. Фотоэлемент же находится в схеме разгрузки образца	(10) Температура 350—1000° С. Точность поддержания температуры ± 2 град. Максимальная нагрузка 50000 н (5000 кГ). Время нагружения до максимальной нагрузки 5—20 мин. Точность поддержания длины $+0,001$ мм	[58]

Key: (1). Type of unit. (2). Operating principle. (3). Fundamental characteristics. (4). Source. (5). Initial stress is created by tightening nut. Stress is determined from the deformation of standard rod, rigidity - by compliance/pliability of rod. (6). The same. (7). Stress is created by spring whose tension is reached by tightening of nut. (8). Compensating type machine (during elongation of specimen/sample to 0.0002c/c closes contact, which through relay gives into action engine, which weakens stretching spring). (9). FEL-5 (VEB-Werkstoffpruflaschenen, GER, Leipzig). (10). Loading with the aid of springs. A change in the length of specimen/sample is transferred through quartz rods to the linkage, gauging the position diaphragm, in turn, which affects the flow of the world/light, falling/incident to photocell. Photocell is located in the schematic of unloading specimen/sample. (11). Temperature of 350-1000°C. Accuracy/precision of the maintenance of temperature of ± 2 deg. Peak load 50000 n (5000 kgf). Time of loading to peak load 5-20 min. Accuracy/precision of the maintenance of the length of ± 0.001 mm.

continuation Table 4.

(1) ■ Тип установки	(2) Принцип действия	(3) Основные характеристики	(4) Источник
УИМ-5 (ЦКТИ)	(5) Машина компенсационного типа. Нагружение от бункера с шарами. Разгрузка происходит по достижении заданной деформации путемброса шаров по одному через равные промежутки времени. Исключена возможность докладки образца во время испытания	(6) Максимальная нагрузка 40000 кг (4000 кН). Отношение плеч рычага 1:50, рабочая температура 400—750°C, точность поддержания длины образца 0,002 мм	[63]
УИМ-5 (ЦКТИ)	(7) Машина того же типа. Нагрузка шарами заменена нагружением от червячного устройства через фрикцион	(8) Нагрузка 3500—40000 кг (350—4000 кН). Температура до 900°C, точность поддержания длины образца 0,001 мм	[55]
ИП2 (ЦНИИТ- МАШ)	(9) Нагружение с помощью червячно-винтового устройства. Нагрузка фиксируется кольцевым динамометром. При изменении деформации образца производятся повторные докладки	(10) Максимальная нагрузка 30000 кг (3000 кН). Температура до 900°C	[64]
5ИМ (ЦКТИ)	(11) Машина компенсационного типа нагружена с помощью груза, перемещающегося вдоль рычага. По достижении определенной пластической деформации срабатывает электромагнитное реле, включается электродвигатель, который перемещает груз	(12) Максимальная нагрузка 50000 кг (5000 кН). Точность поддержания длины образца 0,04—0,008%. Скорость нагружения 30 Мн/м² (3 кГ/мм²) в 1 сек. Скорость разгрузки 12,5 Мн/м² (1,25 кГ/мм²) в 1 сек	[67]

Key: (1). Type of unit. (2). Operating principle. (3). Fundamental characteristics. (4). Source. (5). Compensating type machine. Loading from hopper with spheres. Unloading occurs on the achievement of the assigned/prescribed deformation via the discharge/break of spheres one through equal time intervals. Is excluded the possibility of the additional charge of specimen/sample during testing. (6). Peak load 40,000 N (4000 kgf). Leverage 1:50, working temperature of 400-750°C, the accuracy/precision of the maintenance of the length of specimen/sample 0.002 mm. (7). Machine of the same type. Load by spheres is replaced by loading from the work device through the friction coupling. (8). Load 3500-40000 N (350-4000 kgf). Temperature to 900°C, accuracy/precision of the maintenance of the length of specimen/sample 0.001 mm. (9). Loading with the aid of worm-helical device. Load is record/fixed with the proving ring. During a change in the deformation of specimen/sample, are manufactured repeated additional charges. (10). Peak load 30,000 N (3000 kgf). Temperature to 900°C. (11). Compensating type machine is loaded with the aid of load, which is moved along lever. On the achievement of the specific plastic deformation, wears/operates electromagnetic relay is included the electric motor, which moves load. (12). Peak load 50,000 N (5000 kgf). Accuracy/precision of the maintenance of the length of specimen/sample 0.04-0.1(80,0. Rate of loading 30 MN/m² (3 kg/mm²) 1 s. Rate of unloading 12.5 MN/m² (1.25 kg/mm²) ⁱⁿ 1 s.

continuation Table 4.

(1) Тип установки	(2) Принцип действия	(3) Основные характеристики	(4) Источник
(5) Машина с масляным нагружением	(6) Машина компенсационного типа. На рычаге подвешен масляный бак. При удлинении образца до предельной величины стрелка индикатора замыкает контакт и включает магнитное реле, открывающее кран выпуска масла из бака. Исключена возможность догружения образца		[65]
ПВ-152, ПВ-3012 (НИКИМП)	(7) Нагружение с помощью червячного винтового устройства. Нагрузка фиксируется динамометром или тензодатчиком, наклеенным на упругий элемент	(8) Максимальная нагрузка 30000 н (3000 кГ). Рабочая температура 900—1500 и 900—2500°С. Вакуум $5 \cdot 10^{-4}$ — $5 \cdot 10^{-3}$ н/м ² . Скорость нагружения 2 мм/мин	[66]
(9) Машина Института Физики металлов (УФАИ)	(10) Нагружение пружиной	(11) Максимальная нагрузка 10000 н (1000 кГ). Точность поддержания длины образца 0.0002 мм. Рабочая температура до 900°С. Точность поддержания температуры ± 1 град. Скорость нагружения и разгружения 32 Мн/м ² в минуту (3,2 кГ/мм ² /мин)	[11]

Key: (1). Type of unit. (2). Operating principle. (3). Fundamental characteristics. (4). Source. (5). Machine with cil loading. (6). Compensating type machine. From lever is suspend/hung the oil tank. During the elongation of specimen/sample to limiting value, the arrow/pointer of indicator closes contact and switches on magnetic relay, which open/disclcses the tap/crane of the issue of oil from tank. It is excluded the possibility of loading of specimen/sample. (7). Loading with the aid of worm helical device. Load is record/fixed with dynamometer or strain gauge, stuck on elastic cell/element. (8). Peak load of 30,000 N (3000 kgf). Operating temperature 900-1500 and 900-2500°C. Vacuum $5 \cdot 10^{-4}$ - $5 \cdot 10^{-3}$ N/m². Rate of loading 2 mm/min. (9). Machine of institute of physics of metals. (10). Loading by spring. (11). Peak load 10,000 N (1000 kg). Accuracy/precision of the maintenance of the length of specimen/sample 0.0002 mm. Working temperature of up to 900°C. Accuracy/precision of the maintenance of the temperature of ± 1 deg. Rate of loading and unloading 32 MN/m² per minute (3.2 kg/mm²/min).

continuation Table 4.

(1) Тип установки	(2) Принцип действия	(3) Основные характеристики	(4) Источник
Caubo	(5) Нагружающая система маятникового типа. Длина образца поддерживается постоянной с помощью системы экстензометра, связанного электрически с двигателем нагрузки	(6) Точность поддержания длины образца 0,001—0,002 мм	[56]
Джаназян	(7) Нагружающая система рычажного типа с водяным баком. Сброс воды производится при замыкании электроконтакта индикатора, связанного с электронным реле водосбросного клапана	(8) Время нагружения 2 мин. Проволочный образец длиной 200—900 мм	[58]
Kennedy a. Duglas	(9) Машина с пневматическим двигателем, давление в котором варьируется с помощью регулятора давления и соленоидных клапанов нагрузки и разгрузки	(10) Максимальная нагрузка 45000 н (4500 кГ). Скорость нагружения и разгрузки не более 80 Мн/м ² (8 кГ/мм ²) в минуту	[57]

Key: (1). Type of unit. (2). Operating principle. (3). Fundamental characteristics. (4). Source. (5). Pendulum type loading system. The length of specimen/sample is supported by constant with the aid of the system of the extensometer. of that connected electrically with the engine of load. (6). Accuracy/precision of maintenance of length of specimen/sample 0.001-0.002 mm. (7). Range. (8). Lever/crank type loading system with water tank. The discharge/break of water is manufactured by the closing,shorting of the electric contact of indicator, connected with electronic relay of water-outflow valve. (9). Time of loading 2 min. Wire specimen/sample with a length of 200-900 mm. (10). Machine with air motor, pressure in which is varied with the aid of pressure regulator and solenoid valves of loading and unloading. (11). Peak load 45000 N (4500 kgf). The rate of loading and unloading not more than 80 MN/m² (8 kg/mm²) per minute.

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Let us examine in somewhat more detail the comparatively new construction/designs: machine Rel-5, and also the reconstructed machines UIM-5 [55, 63], SIM [67] and PV152 [66].

The kinematic diagram of the modernized machine UIM-5 is represented in Fig. 17.

A change in the length of specimen/sample 0 causes the closing/shorting of the governing contacts of contact device K, connected with extensometer, and inclusion with the aid of the relay of reversible electric motor M, which rotates worm gear by 7. The rotation/revolution of the axle/axis of 6 worm gears is transferred to large friction roller by 5. To the axle/axis of 4 rollers 5, is wound cable by 3, with the aid of which is moved the end of lever 2. The end of small lever arm 2 through the thrust/rod with built-in dynamometer D is connected with the end of loading lever 1. Thus, depending on the direction of rotation of electric motor the end of the loading lever is moved upward or downward, respectively decreasing or increasing load on specimen/sample. The value of effort/force is recorded by the dynamometer, connected with the diagram mechanism, which realize/accomplishes a recording of the curve of stress relaxation.

Contact device K, which controls load change, has movable and two fixed contacts. The slide contact, which is the small piece of the flattened silver wire, is soldered to the arrow/pointer of indicator. Both of fixed contacts (small silver plate) are fasten/strengthened to the Flexiglas glass, which replaces that covering riding-crop dial. Use as the contact device of indicator

knob/cap with scale value 0.002 mm makes it possible to ensure the constancy of the measured length of specimen/sample within the limits of $\pm 1 \mu\text{m}$ with the total clearance between contacts approximately 1 mm. The closing/shorting of slide contact with one of the fixed contacts causes the rotation/revolution of engine into one or the other side.

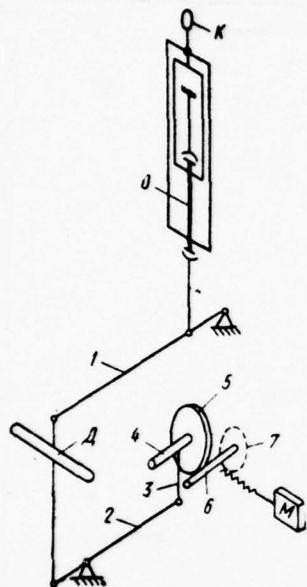


Fig. 17. Kinematic diagram of the modernized machine UIM- 5.

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With the modernization of the loading device, were used the engine and worm gear, which in machine UIM-5 serve for rotating the hopper. Induction motor of the type MSh with a power of 75 W is equipped by the variable resistor, which makes it possible to regulate speed. Reversibility is achieved by a change in the schematic of the feed of the brushes of engine. For the reversal of load introduced additional relay, which wear/operates from the closing/shorting of the second fixed contact. The gear ratio of worm

gear is equal to 100. Large friction roller 5 is textolite disk with the mounted steel ring. The diameter of cylinder 4, to which is wound cable by 3, is equal to 4.3 mm, the diameter of flexible cable 1.5-2 mm. For providing friction coupling one of the bearings in which is rotated shaft by 4, it moves freely in vertical direction. With stretching of cable 3, is created the contact pressure between the friction rollers, proportional to tension.

This pressure the minimum 95 times more than circumferential force in the friction coupling, which guarantees the absence of slippage with any tension of cable.

So that the cable would be wound around cylinder by 4 in one circumference independent of the angle of ascent of lever 2 (this is required for the exception/elimination of the possibility of the axial slip of cable along cylinder 4), the joint of cable with lever is made movable. Toward the end of the cable, is fastened horizontal axis with the sitting on it two bearings on which rests lever by 2. For the elimination of side bearing load during the deviation of lever from horizontal, the bearing surface of lever is carried out in the form of involute. Evclvent surface intersects the plane of the winding/coil of cable at right angle in any position of lever; therefore the direction of the effct/force, which acts on bearings from the side of lever, coincides with the axle/axis of cable. In

connection with the noticeable curvature of evclent surface, the bearings with sufficient precision "find" necessary position, providing the correctness of the winding/ccil of cable.

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The relationship/ratio of lever arms 2 (see Fig. 17) is equal into average 1:5. The support of lever is fasten/strengthened to the plate/slab (from the sheet with a thickness of 10-15 mm), conducted under the engine bed and rigidly connected with it by the means of anchor bolts. The second end of lever 2 with the aid of link is connected with the threaded knob/cap of dynamometer D. Another threaded knob/cap is connected with the end of loading lever 1.

Flat/plane dynamometer is calculated for continuous operation under the action of maximum effort/force 0.8 MN (80 kgf), which corresponds to the load, which somewhat exceeds maximum rated load on specimen/sample [40 MN 4000 kg]. With load 0.8 MN (80 kgf) the sagging of the bracket of dynamometer composes in calculation 4 mm, and the maximum stresses in bracket - about 400 MN/m^2 (40 kg/mm^2). The bracket of dynamometer is made of steel 25Kh2MFA, heat-treated to hardness 37-39 HRC, which corresponds to yield point of approximately 1000 MN/m^2 (100 kg/mm^2). Thus, operating stresses have a supply on yield point of approximately 2.5. Dynamometer is

equipped by indicator with scale value 0.01 mm, which provides accuracy of reading 0.25% of peak load.

Device for the automatic recording of load consists of drum clockwork with weekly plant and diagram pen. By Perot it is fasten/strengthened to fine/thin filament, which is wound around the Flexiglas block, fasten/strengthened to the axle/axis of the indicator of dynamometer. Thus, load change, calling the rotation of the arrow/pointer of indicator, leads also to the vertical displacement of pen. Since the characteristic of dynamometer is linear, the shift of the pen is strictly proportional to load. Entire system is counterbalanced so that the axle/axis of indicator does not experience/test the bending loads. Drum is placed above loading lever 1 (see Fig. 17) and it is fasten/strengthened to traverse, connected with thrust/rod of the dynamometer. This fastening is necessary for slope deviation of loading lever 1 would not affecting the position of drum.

Dynamometer and diagram device are calibrated in machine with the aid of the specimen dynamometer, fastened instead of specimen/sample and capture of machine. On the data of calibrating, are constructed the calibration curve/graphs which allow from readings of dynamometer and from diagram to design load for specimen/sample in the process of testing.

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For the normal operation of the loading device, the angle of the slope of lever 2 must be within the limits of 0-55° from horizontal; the respectively maximum permissible course of cable comprises ~150 mm. This course insufficient for providing the necessary to degree unloading of specimen/sample in the process of testing. Furthermore, the oscillations of temperature of location cause the deformation of mounting and external parts of the captures. This occurring in this case change in the tension of specimen/sample is automatically compensated for by the appropriate displacement of lever. These facts can derive lever 2 of the normal position and disturb the correct rhythm of the work of machine. In order this to avoid, on lever is establishinstalled the relay, with the aid of which is supplied the signal (bell), which indicates the approach/approximation of lever to end upper or lower position. With the inclusion of bell, is stopped the engine. The translation/conversion of lever 2 into normal position (angle of ascent of 35-45°) is realize,accomplished by steady tightening or weakening of chain/network with the aid of the handle of the reducer of lower capture. Since the length of specimen/sample is automatically supported by constant, the with the aid of engine respectively is lower/omitted or is raised lever.

The maintenance of machine with loading device indicated above consists of observation of the temperature of specimen/sample, periodic recording of readings of the indicator of dynamometer and in rare cases in tightening or weakening of chain/network with specimen/sample. Initial tension to specimen/sample is assigned as follows. Lever by 2 is changed into end upper position. From indicator K, is remove/taken the fixed contact, governing an increase in the load. By the rotation of display scale of rifleman/gunner it is combined with the division, which corresponds to the assigned/prescribed deformation of specimen/sample (the fixed contact, governing unloading, it is establishinstalled on indicator so that with the contact with it of slide contact arrow/pointer is combined with zero mark). Then with the aid of reducing motion they tighten chain/network. In this case, the arrow/pointer of indicator K moves to the contact of contact, fasten/strengthened to it, with fixed contact. At this moment is reached the assigned/prescribed deformation and engine it comes into action, unloading specimen/sample.

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The second fixed contact is establishinstalled on indicator so that

the total clearance would comprise 1 mm. After this the loading device works automatically.

The kinematic diagram of the relaxation machine 5IM, also designed by N. D. Zaytsev, is given in Fig. 18. It is characterized by high rate of loading and unloading, which makes it possible to study short-term stress relaxation at high temperatures. Testing in machine manufactures as follows.

Heating specimen/sample by 8 is manufactured in electric furnace by 9.

After the achievement of necessary temperature of load 1 is established/installer in lever 2 at a distance, which corresponds to the assigned/prescribed initial voltage; the electrical contact of 3 levers of extensometer occupies the free position in the narrow clearance between fixed contacts 4 and 5. Loading is realized/accomplished relieving the lever from detent 6. Simultaneously by the rotation/revolution of micrometer gauge 7 is supported the established/installer position of contact 3. At the moment of separation of lever from detent, is connected the feed of engine and diagram mechanism. The drum of diagram apparatus is rotated from the selsyn of 15 gearboxes 18 ($v=500 \text{ mm/h}$). Subsequently the process of relaxation and recording changes of the residual

stress with time occur automatically.

With the accumulation of the plastic deformation of the specific value, the position of extensometer 19 is changed, which leads to closing of contacts 3 and 5 and functioning of electromagnetic relay. Under the action of the mercury contact of 14 relays, it is closed, the circuit of electric motor 13 and load are moved to the side of the decrease of load, as a result of which the stress descends, specimen/sample is reduced by initial length, the contact of extensometer comes to initial position and again begins the process of relaxation in specimen/sample, but already with the smaller stretching force, etc. Simultaneously with weight shifting during the rotation/revolution of electric motor is rotated the rotor of the selsyn, attached on the arrow/pointer or lever. The selsyn of lever is electrically connected with the selsyn of the displacement of the pen of 16 diagram mechanisms, in consequence of which with drum 17 is recorded load change in the process of testing.

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The loading of specimen/sample in machines of the type Rel-5 manufactures with the aid of double-armed lever. Leverage is connected with the pair of the springs which can be replaced depending on the required range of loads [2500-12,500, 5000-2500,

10,000-50,000 N (250-1250, 500-2500, 1000-5000 kgf)].

The springs through the screw/propeller, the worm-and-worm wheel and belt drive are connected with engine, the rotation/revolution of screw/propeller leads to stretching or relaxing of spring and with respect to loading or unloading of specimen/sample. The system of loading is conjugate/combined with the recording diagram tool, which records a change in the load with time.

Measurement and transmissions of deformation manufacture with the aid of three quartz rods of extensometer. The amount of deformation is determined by measuring microscope with helical ocular micrometer. For automatic load dispatching, which acts on specimen/sample, the measured deformation is converted into electrical signal with the aid of the sensor of photocell. The light beam, directed by the projection lamp through the objective toward photocell, is diaphragmed in the focus of objective by the special shutter, fixed toward the end of the lever/crank system of the extensometer. Under conditions of compensation, the shutter stops photocell approximately half.

The sensor of photocell is fed by stabilized voltage. Changes in the current of photocell are transferred to the electron-tube bridge which in turn, during imbalance transfers the appropriate signal of

relay and block to the contacts of the system of load dispatching, which acts on specimen/sample.

The loading of specimen/sample up to the assigned/prescribed initial deformation occurs with the aid of measuring microscope.

For high-temperature relaxation tests in vacuum, were adapted the machines of the type FV-152 and PV-3012 for tests for stress-rupture strength [66]¹.

FOOTNOTE¹. I. L. Baptianov et al. Patent certificate No of 160891. Bulletins of invent. and innovations, 1964, No 5, p. 64. ENDFOOTNOTE.

The machines indicated have vacuum chamber for the radiation heating of specimen/samples by tungsten rod heaters to temperature of 2000°C.

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Loading device is the lever/crank type (gear ratio to 1:60). Constant temperature is maintained by voltage regulation with the aid of the special blocks of control, which do not allow/assume the oscillations of temperature during testing not more than $\pm 2^{\circ}\text{C}$.

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Machines are equipped by device for the automatic displacement
of upper capture in a rate of 2 mm/min during heating and cooling the
specimen/sample without the disturbance of vacuum tightness of
system.

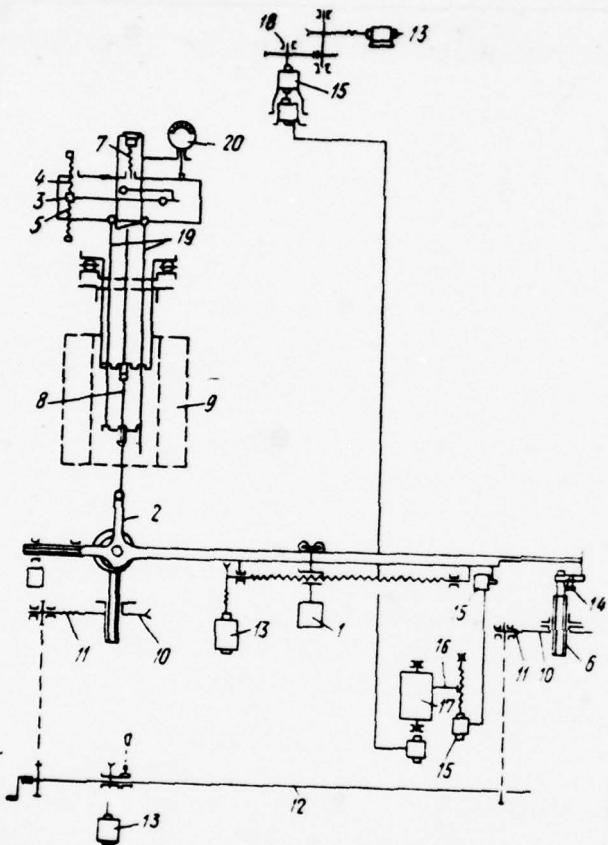


Fig. 18. Kinematic diagram of machine 5IM for tests for relaxation.

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The modification of the kinematic diagram of machines PV-152M and PV-3012 for test work for relaxation consisted of disassembly the systems of loading, unit of elastic cell/element with strain gauges and rigid fastening of chair/network with elastic cell/element to

sounting.

Specimen/sample 1 (Fig. 19) is attached into upper 2 and lower 3 captures from molybdenum alloy can freely be expanded during heating. Upper catch through adapter 4 is connected with supporting/reference hinge joint by 5, and lower - by connecting rod 6 through elastic cell/element 7 with machine frame.

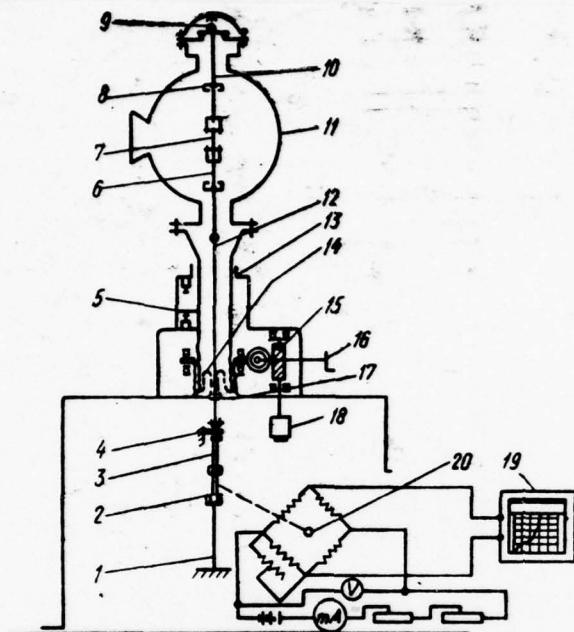


Fig. 19. The kinematic diagram of machine FV-152M for relaxation tests: 1 - thrust/rod lower; 2 - elastic cell/element; 3 - thrust/rod upper; 4 - detent; 5 - position indicator of elevating screw; 6 - capture lower, 7 - specimen/sample; 8 - capture upper; 9 - hinge joint special; 10 - adapter; 11 - electric furnace; 12 - thrust/rod of lower capture; 13 - screw/propeller lift; 14 - bellows; 15 - reducer; 16 - handle of the manual displacement of screw/propeller; 17 - diaphragm; 18 - electric motor; 19 - electronic potentiometer; 20 - extensometric bridge.

Thrust/rod is consolidated with the aid of the rubber blanket. The loading of specimen/sample is manufactured automatically by lifting the furnace body from electric motor 8 or by hand by handle 9 through reducer 10.

Elastic cell/element is made in the form of plate by section/cut 2x1 mm² for loads to 2000 N (200 kgf) and 7x7 mm² for loads to 10,000 N (1000 kgf). The application/use of different elastic cell/elements and specimen/samples of different section/cuts makes it possible to experience/test refractory metals under conditions of relaxation with different rigidity of loading. The rigidity of loading is determined by the compliance/pliability of the furnace body and grips. For test work under conditions of high rigidity, it is necessary to utilize specimen/samples with low cross section. The rigidity of loading can be determined according to a change in the length of the working part of the specimen/sample, measured with the aid of cathetometer.

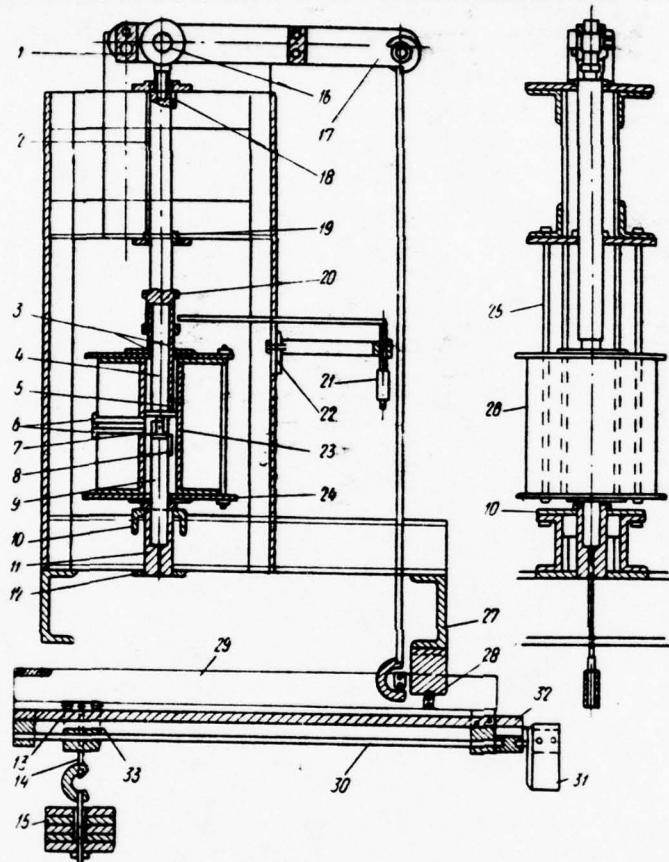
Resistance strain gauges of 100 ohms with base 15 mm were made from constantan and they had a coefficient of strain sensitivity 2-2.2. The temperature compensation (for the exception/elimination of the effect of the oscillations of location temperature) was achieved by the inclusion into symmetrical bridge arms 11 (see Fig. 19) constantan resistances. The feed of bridge was realized/accomplished by a direct current 4-8v from batteries. Operating current was 15-90

mA depending on the range of calibrating.

Calibrating elastic cell/element to 2000 N (200 kgf) was manufactured by the method of direct loading by the load of the specific mass, in this case, they establish, installed the dependences of the readings of electric potentiometer 12 (EPP-09) on the value of load. Calibrating strain gauge to 5000 and 10,000 N (500 and 1000 kgf) manufactured on the specimen dynamometer, built-in into the chain/network of loading. Chain/network with the calibrated elastic cell/element assembled in such a way that with the evacuation of the camera/chamber there would not be the lift of down-draft 13 under the action of atmospheric pressure; the appearing effort/force was absorbed by elastic cell/element and electric potentiometer record/fixed the value of vacuum load.

Relaxation test is realized/accomplished as follows.

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19 - insert; 20 - extensometer with the sliding half-sleeves; 21 - knob/cap of micrometer; 22 - adjustable guides; 23 - guide; 24 - end of the furnace, 25 - stem guide furnaces; 26 - furnace; 27 - channel bar; 28 - the knife edge; 29 - lower lever; 30 - shaft with the square thread; 31 - electric motor; 32 - rail; 33 - driving/moving plate.

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After the achievement of the assigned/prescribed temperature¹ and of the establishment of the current strength of the assigned magnitude, they are included the electromechanical drive of the lift of furnace 14 (with a rate of climb of 2 mm/min) and the drive of the diagram of the potentiometer EPP-09.

FOOTNOTE 1. Before beginning testing, it is necessary to be convinced of the warming up of all elements of system. ENFOOTNOTE.

On the achievement of the load of the assigned magnitude, the drive of the lift of furnace is disconnected and on diagram automatically is record/written relaxation curve.

For relaxation tests under conditions of compression, was proposed the construction/design of unit UMIR-10 in power 10 t [65].

Specimen/sample lies/ rests on roller supports and it can be moved on the planes of contact with support. The greater the stress in specimen/sample, the greater the forces necessary for the overcoming the forces of friction. The voltage drop during testing is measured according to a change in forces of friction.

The machine, used in work [68] for the tests of cast iron for relaxation under conditions of compression (Fig. 20), was created on the basis of the creep device. The specimen/sample, which is cylinder with a diameter of 6.35 by the height of 25.4 mm, is compressed between two rods whose end/faces have the ground lapped finish. Load is applied with the aid of linkage. Deformation is measured by the special extensometer, which increases 5 times displacement with the aid of linkage. The maintenance of deformation at the assigned/prescribed level is achieved by weight shifting along the loading lever, realized/accomplished with the aid of servomotor and screw/propeller.

The system indicated is characterized by following parameters: the rate of engine 1.5 r/min, propeller pitch 25 mm, the displacement of the end of the lever of extensometer on 0.0075 mm leads to a change in the stress in specimen/sample on 0.84 MN/m (0.084 kg/mm²).

Initial loading is realize/accomplished by a loosing of closing screw under the end of the lever in which establish/install in suspension the necessary for the creation of the assigned/prescribed initial voltage loads. Simultaneously with unscrewing of screw/propeller is screwed in micrometer before the appearance of a contact with the lever of extensometer. In this case, wear/operates with relay and begins the process of testing.

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2. Relaxation with bend and twisting.

Great application/use they found two methods of relaxation tests during bending: annular specimen/samples [69] and flat springs [52, 70]. I. A. Oding's method [69], which is in our laboratories virtually basic for obtaining the resistance characteristics of the relaxation of materials, consists of following: the annular specimen/sample, constructed in the form of fish-bellied bar to bending (Fig. 21), they load with the aid of the wedge of the specific thickness, inserted into gash. Specimen/sample with wedge places into heating device (furnace or fluid bath), where in time occur the processes of relaxation of initial stresses. The assigned/prescribed initial voltage is created by the selection of the thickness of wedge. The value of the relaxed stress they determine with respect to a change in the initial width of gash. Stresses are determined on the formulas

$$\sigma_0 = AE_T \Delta, \quad (102)$$

$$\Delta\sigma = AE_T \Delta_1, \quad (102a)$$

where A - the constant, obtained from the condition of the linear distribution of stresses over the mean section of specimen/sample [69] ($A=0.000583 \text{ mm}^{-1}$); E_T - modulus of elasticity at testing temperature; Δ - change in the width of gash because of the setting up of wedge; Δ_1 - change in the initial width of gash because of creep.

Method has the following limitation: if initial stress σ_0 equals to or exceeds elastic limit (proportionality) of material at testing temperature, then instantaneous plastic deformation sharply changes actual value σ_0 [then, plastic defcirmation 0.5% it leads to decrease σ_0 to 85 MN/m^2 ~~8.5 kg/mm}^2~~].

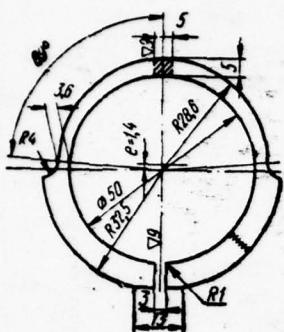


Fig. 21. Ring for relaxation tests according to the method of Odinc.

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In connection with this the tests of annular specimen/samples are possible with σ_0 , equal to $\leq 0.75 - 0.8 \sigma_{0,2}^T$. But also when $\sigma_0 = 0.8 \sigma_{0,2}^T$ in a number of cases are possible the errors into connection with plastic deformation at room temperature, this is observed under the condition

$$\frac{\sigma_{0,2}^{20^\circ\text{C}}}{\sigma_{0,2}^t} < \frac{E_{20^\circ\text{C}}}{E_t}. \quad (103)$$

This condition is satisfied, for example, for steels EI612 and EI787 with 650-700°C.

During the tests of annular specimen/samples, the accuracy/precision of the calculation of drops in stress, according to formula (102), depends on the authenticity of the determination of the values of the moduli of elasticity. at present widely are utilized two methods of determining the modulus of elasticity: static and dynamic.

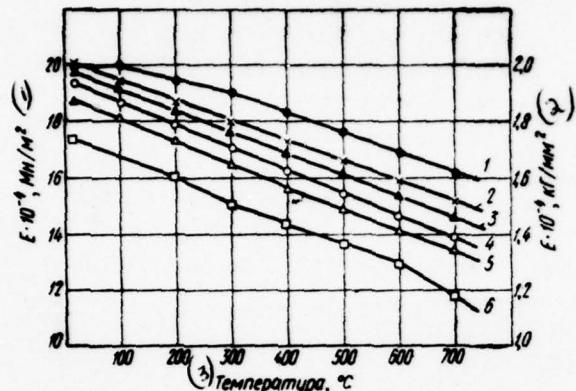


Fig. 22. A change in the modulus of elasticity of steels EI612 and EI481 in dependence on temperature, determined by dynamic (1-5) and static methods (6), obtained in various laboratories: 1, 3, 4 - in ~~in~~ TsNIITMASH; 2 - in TSKTI; 5 - in Institute im. Baranov; 6 - in VIAM [BHAM - All-Union Scientific Research Institute of Aviation Materials].

Key: (1). MN/m². (2). kg/mm². (3). temperature.

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The time of measurement and the range of the utilized stresses virtually exclude the possibility of course of the processes of creep with dynamic (E_{dyn}) and static (E_{st}) the methods of determining the modulus of elasticity. However, the difference between values E_{dyn} and E_{st} , reaches sometimes 200%. Furthermore, certain differences in

the values of the modulus of elasticity are observed during its determination in the specimen/samples of different size/dimensions, on metal of different meltings, with an equal reduction in forging, etc.

Figures 22 as an example gives dependence curves of the modulus of elasticity of steels EI481 and EI612, obtained by different methods, in different laboratories.

At the same time in the reference literature of the value of the modulus of elasticity of different materials, they are brought, as a rule, without the indication of the method of its determination. This in turn, can lead to faulty conclusions with comparison of the resistance characteristics of the relaxation of different materials. Therefore this comparison, apparently, can be carried out only during the use of values of E of the compared materials, determined by identical methods.

Are known the methods of the recalculation of the results of the tests of circular samples for the case of uniaxial stressed state [43, 71-73]. V. I. Roserblum [43] will propose solving the problem of the redistribution of the stresses in bent bar, utilizing a hypothesis of flow. I. A. Odintsov and G. F. Lepin [71] will conduct the appropriate calculations on the basis of the assumption about

transformations in the process of the relaxatio~~n~~ of triangular diagram/curve into trapezoidal.

The original method of calculation of changes of the stresses in annular specimen/sample was proposed by Ye. A. Heyn [72, 73], who examines the problem of stress relaxation in rectangular bar with pure bending. In this case all cell/elements of the volume are located in pure stress.

At the any moment of time τ , the stress distribution in specimen/sample $\sigma(y)$ unambiguously depends on initial stress. With the first of loading $\sigma_0(y) = k\sigma_0^{\max}$.

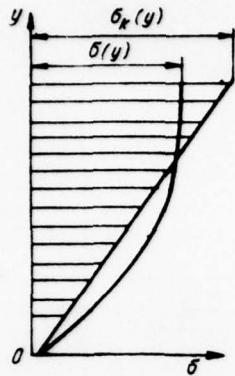


Fig. 23. Schematic of the stresses in the section/cut of annular specimen/sample.

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After designating $\sigma_k(y)$ — stress of triangular diagram/curve, to same-moment true stress diagram (Fig. 23), we will obtain

$$\int_0^y \sigma(\xi) \xi d\xi = \frac{1}{3} \sigma_k(y) y^2. \quad (104)$$

Will differentiate both of parts of equation (104) on y

$$\sigma(y) = \frac{2}{3} \sigma_k(y) + \frac{1}{3} y \frac{d\sigma_k(y)}{dy} \quad (105)$$

and after conducting elementary conversions, we will obtain

$$\sigma(\sigma_0) = \frac{2}{3} \sigma_k(\sigma_0) + \frac{1}{3} \sigma_0 \frac{d \ln \sigma_0}{d \ln y} \cdot \frac{d\sigma_k}{d\sigma_0}. \quad (106)$$

For first loading $\frac{d \ln \sigma_0}{d \ln y} = 1$ and

$$\sigma(\sigma_0) = \frac{2}{3} \sigma_k(\sigma_0) + \frac{1}{3} \sigma_0 \frac{d\sigma_k}{d\sigma_0}. \quad (107)$$

For the calculations of n- loading according to formula (106) it is necessary to know the value of initial stress σ_{0n} , which they determine consecutively from the formula

$$\sigma'_{0n} = \sigma'_{n-1} + (\sigma'_{0n} - \sigma'_{n-1}) \frac{\sigma'_{01}}{\sigma'_{01}}, \quad (108)$$

brought out made suppositions of the transformation of the transverse size/dimension of specimen/sample 2h:

$$\frac{h''}{h'} = \frac{\sigma'_{01}}{\sigma'_{01}},$$

where σ'_{0n} and σ'_{0n} — initial stress with the n loading for specimen/samples with initial stresses with the first loading σ'_{01} and σ''_{02} ; σ'_{n-1} and σ'_{n-1} — final stresses with (n-1)th loading for specimen/samples with initial stresses with the first loading σ'_{01} and σ''_{01} .

Figure 24 gives the procedure for calculation of initial stresses according to equation (108) for the second loading and the graphic method of calculation of actual stress according to formula (107).

Calculations [73] conducted will show that the curves of relaxation 1, calculated by formulas (102), (102a), for the first loading were close to curved 4, obtained on formula (107). After repeated loadings the curves indicated sharply are distinguished: the true curve of uniaxial relaxation prove to be itself that below found from formulas (102), (102a) (Fig. 25). Curves 2, calculated by the hypothesis of trapezoid [71], prove to be themselves below true for the first and repeated loadings. The curves of relaxation 3, calculated according to the theory of flow [43], will prove to be also close to true.

Considerably smaller propagation will obtain another testing method for relaxation with tending, developed in TsNIITMAShe [24].

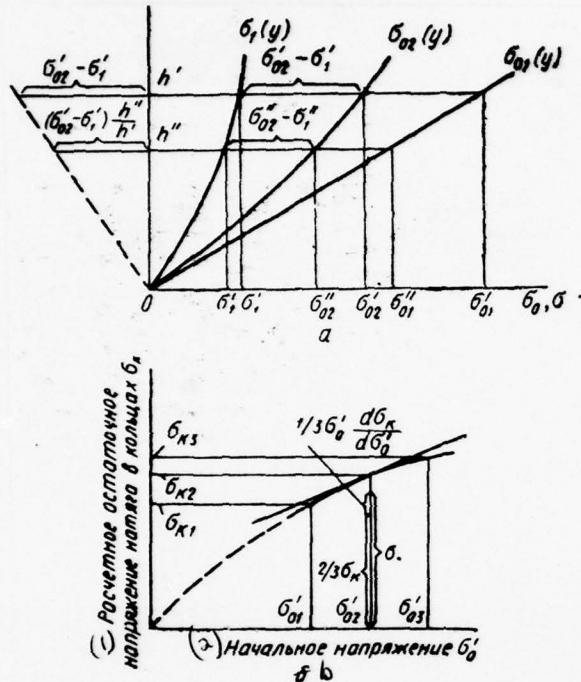


Fig. 24. Procedure for calculation of initial stresses according to equation (108) for the second loading (a) and the graphic method of calculation of actual stress (b) [73].

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Testing is subjected the flat/plane plate by which is assigned certain sagging/deflection. Operating principle of the special device of IR-4N, created for such tests, that follows. Hammers of attachment, which create the necessary sagging of plate, select depending on the value of the assigned/prescribed initial voltage. the rotation of cam/catch/jaw on 90° provides the creation of the sagging/deflection of two simultaneously tested springs.

Cam/catch/jaws after heating of attachment turn with the aid of special key/wrench. Unloading specimen/sample is manufactured by the same key/wrench.

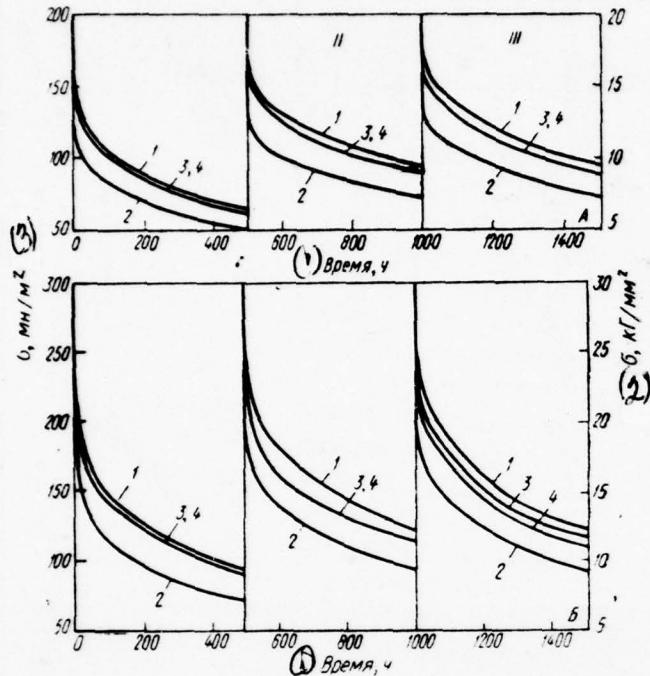


Fig. 25. The curves of stress relaxation, calculated by test data of annular specimen/samples [73]: A, B - $\sigma_0 = 200$ and 300 mN/m^2 (20 and 30 kg/mm^2) respectively; I, II, III - first, second and third insertion respectively.

Key: (1). Time, h. (2). kg/mm^2 . (3). MN/m^2 .

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Stresses calculate from the formulas

$$\sigma_0 = \frac{6Eh}{l^2(1-\mu^2)} f_0, \quad (109)$$

$$\sigma_k = \frac{6Eh}{l^2(1-\mu^2)} f_k, \quad (110)$$

$$f_k = f_0 - (f_k)_{ns}, \quad (111)$$

where f_0 - initial elastic deflection; $(f_k)_{\text{pa}}$ — permanent deflection;
 l — length of plate; h — thickness; μ — Poisson ratio.

For measurement $(f_k)_{\text{pa}}$ is utilized special electromicrometer.

A deficiency in the method is difficulty in the manufacture of plates, especially in the case of nonmagnetic material.

In work [74] are compared the characteristics of relaxation, determined by the methods of ring testing of equal strength bending also of flat springs. The calculations of the stresses in annular specimen/samples for steel of 25Kh2M1F carry out without taking into account of their redistribution through section/cut. Table 5 gives corrected values of remaining stress σ_r for 1000, 3000, 5000 and 10,000 h, and also values of the relaxation time, calling reduction σ_0 to values $\sigma_r = 100(10)$ MN/m² (kg/mm²) ($\theta_{\sigma=20}$ and $\theta_{\sigma=10}$). The parameters, characterizing first and the second the stages of relaxation, are designated as σ'_0 , S_0 and θ_0 , where σ'_0 — conditional initial stress of the second stage, $S_0 = \sigma'_0 / \sigma_0$; θ_0 — coefficient of

the intragranular stability of materials.

Table 5 shows that values σ_r for rings and springs do not coincide, the difference between those indicated to values having different sign in dependence from the temperature of testing and initial stress.

One should note also the different behavior in the first and second stages of the process: values $S = \sigma'_{\infty} / \sigma_0$ for flat springs, as a rule, are more than for circular samples, but values θ , characterizing the intensity of relaxation on the second section, on the contrary, for the tests of flat springs are less than for annular specimen/samples.

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The comparison of the characteristics of relaxation, found in tests for elongation and bending (with the aid of annular specimen/samples without taking into account of the redistribution of stresses), is conducted in a series of works [75, 76].

The comparison of the characteristics of relaxation, found in experiments to elongation and bending (with the aid of annular specimen/samples without taking into account of the redistribution of

stresses), is conducted in a number of works [75, 76].

Was reveal/detected that in circular samples at the initial stage of process is observed a more intense reduction in the stresses in comparison with cylindrical ones. However, values σ_t after 200-1000 h will prove to be close between themselves [37].

Analogous conclusions it is possible to make on Table 6.

being of limited usefulness will obtain also the methods of testing from the bending of specimen/samples in the form of the metallic film/strip, proposed in connection with spring film/strips [87, 88]. The essence of method consists of following.

Spring film/strip introduces into the steel rings whose bore diameter selects in accordance with initial stress. The size/dimensions of rings must provide obtaining only elastic deformation. The "charged" rings age/hold at the temperature of testing for a period of time, necessary for the plotting of curves of relaxation. The method of heating rings with film/strip, just as the method of heating the annular specimen/samples of Oding, selects depending on those requirements which places upon himself the researcher in the ratio/relation to the thoroughness of the study of the first section of relaxation. If necessary of determining the

residual stress through several minutes after loading is applied the heating in the fusion/melt of salts whose composition selects in connection with testing temperature. For carbon steel and steels with the limited quantity of nickel, is feasible more intense heating - in the fusion/melt of pure lead or its eutectics. Tests at the temperatures, not calling the intense development of the processes of creep, carry out with heating in furnace. Residual stress determines according to the measurements of the radius of curvature of film/strip, extracted from ring, with the aid of the formula

$$\sigma = E \frac{h}{2} \left(\frac{1}{\rho_0} - \frac{1}{\rho_p} \right), \quad (112)$$

where h - thickness of belt; ρ_0 - radius of ring; ρ_p - radius of curvature of belt, deformed during relaxation.

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Table 5. Comparison of the results of relaxation test of steel of
25Kh2M1F.

Temperature (°C)	(1) σ_0	(2) σ_{100}		(3) σ_{500}		(4) σ_{5000}		(5) σ_{10000}		$\theta_{\sigma=200}$		$\theta_{\sigma=100}$		(6) σ'_0		S_s	$\theta_{\sigma, r}$
		MN/m ²	kg/mm ²	MN/m ²	kg/mm ²	MN/m ²	kg/mm ²	MN/m ²	kg/mm ²	MN/m ²	kg/mm ²	MN/m ²	kg/mm ²	MN/m ²	kg/mm ²		
500	250	25	177 185	17.7 18.5	160 172	16.0 17.2	150 165	15.0 16.5	133 140	13.3 14.0	80 35	19 600 21 500	174 190	17.4 19.0	0.70 0.79	36 000 30 000	
	300	30	212 228	21.2 22.8	192 212	19.2 21.2	182 200	18.2 20.0	157 165	15.7 16.5	2400 4900	25 000 23 000	208 235	20.8 23.5	0.70 0.78	36 000 28 000	
	350	35	246 260	24.6 26.0	226 235	22.6 23.5	219 225	21.9 22.5	185 187	18.5 18.7	7700 8000	31 200 26 000	245 260	24.5 26.0	0.70 0.74	34 000 29 000	
	250	25	148 152	14.8 15.2	124 120	12.4 12.0	110 105	11.0 10.5	92 78	9.2 7.8	35 20	8000 5800	139 140	13.9 14.0	0.55 0.56	24 000 17 000	
	300	30	175 188	17.5 18.8	134 148	13.4 14.8	126 130	12.6 13.0	103 90	10.3 9.0	425 500	10 400 8 600	150 180	15.0 18.0	0.50 0.60	26 000 16 000	
	350	35	215 210	21.5 21.0	170 155	17.0 15.5	152 135	15.2 13.5	120 95	12.0 9.5	1500 1250	14 000 9 200	188 190	18.8 19.0	0.52 0.54	22 500 15 000	
550	250	25	106 120	10.6 12.0	76 88	7.6 8.8	63 75	6.3 7.5	41 52	4.1 5.2	15 20	1200 1900	96 108	9.6 10.8	0.38 0.43	13 000 14 000	
	300	30	131 135	13.1 13.5	90 98	9.0 9.8	79 88	7.9 8.8	58 64	5.8 6.4	200 50	21 000 3200	106 118	10.6 11.8	0.35 0.40	17 000 15 000	
	350	35	146 158	14.6 15.8	102 106	10.2 10.6	87 89	8.7 8.9	62 64	6.2 6.4	250 400	3100 4000	126 125	12.6 12.5	0.36 0.36	16 000 14 000	

Note. In numerator - annular specimen/samples, in denominator - spring.

Key: (1). Testing temperature, °C. (2). MN/m². (3). kg/mm². (4).

h.

FOOTNOTE¹. In certain cases it is obtained by the method of extrapolation.

2. In all cases it is obtained by the method of extrapolation. ENDFOOTNOTE.

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Table 6. Comparison of the results of relaxation tests of annular and cylindrical specimen/samples during equal initial deformation ε_0

(1) Сталь	Температура, °C	ε_0 , %	(3) σ_T , МН/м ² (3)			(4) кГ/мм ² , за время, ч			(5) σ_K/σ_T за время, ч		
			100	1000	3000	100	1000	3000	100	1000	3000
20Х3МФ (ЭИ415)	500	0,100	<u>123 (12,3)</u> 117 (11,7)	<u>115 (11,5)</u> 103 (10,3)	<u>107 (10,7)</u> 100 (10,0)	1,05	1,10	1,07	1,05	1,10	1,07
		0,150	<u>183 (18,3)</u> 175 (17,5)	<u>170 (17,0)</u> 155 (15,5)	<u>160 (16,0)</u> 150 (15,0)						
		0,176	<u>210 (21,0)</u> 200 (20,0)	<u>195 (19,5)</u> 180 (18,0)	<u>190 (19,0)</u> 180 (18,0)						
1Х12ВМФ (ЭИ802)	560	0,100	<u>82 (8,2)</u> 82 (8,2)	<u>57 (5,7)</u> 65 (6,5)	<u>43 (4,3)</u> 52 (5,2)	1,0	0,88	0,83	1,0	0,87	0,80
		0,150	<u>120 (12,0)</u> 120 (12,0)	<u>85 (8,5)</u> 98 (9,8)	<u>62 (6,2)</u> 77 (7,7)						
3Х19Н9МВБТ (ЭИ572)	560	0,175	<u>140 (14,0)</u> 140 (14,0)	<u>100 (10,0)</u> 104 (10,0)	<u>73 (7,3)</u> 85 (8,5)	1,0	0,96	0,86	1,0	0,87	0,80
		0,100	<u>107 (10,7)</u> 122 (12,2)	<u>80 (8,0)</u> 80 (8,0)	—				0,88	1,0	0,83
	600	0,150	<u>150 (15,0)</u> 150 (15,0)	<u>120 (12,0)</u> 120 (12,0)	—	—	—	—	1,0	1,0	1,0
	650	0,100	<u>90 (9,0)</u> 90 (9,0)	<u>60 (6,0)</u> 60 (6,0)	—	—	—	—	1,0	1,0	1,0

Note. In numerator are shown the values for annular specimen/samples

in denominator - for cylindrical ones

Key: (1) - Steel. (2) - Temperature, °C. (3) - MN/mm². (4) - kg/mm². (5) - for time, h.

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Calculations according to formula (112), just as on formula (102a) for the annular specimen/samples of Cding, they propose the triangular diagram/curve of the distribution of stresses over section/cut.

For the investigation of stress relaxation into the process of rapid heating metal (to 2000 deg/s) was developed procedure [77], making it possible to experience/test under conditions of bending the flat/plane plates, heated by the transmission of current.

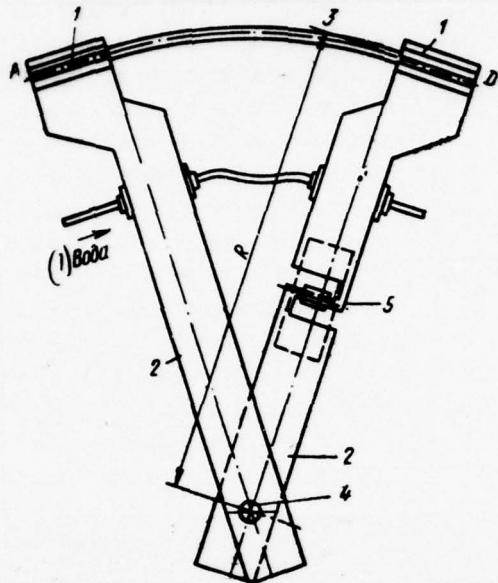


Fig. 26. Diagram of installation [78].

Key: (1). water.

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during these tests are decreased the stresses in the process of heating because of relaxation of stresses at variable temperature and of decrease of the modulus of elasticity during an increase in the temperature:

$$\sigma = \sigma_0 - \epsilon_0 \Delta E - \epsilon_p E_T, \quad (113)$$

where

$$\Delta E = E_{20} - E_T; \epsilon_p = \epsilon_{nn} + \epsilon_n,$$

moreover σ_0 - initial elastic stress with 20°C; ϵ_p - plastic deformation at temperature T, which is composed from creep strain ϵ_n and of instantaneous plastic deformation ϵ_{nn} .

Original setting up is created by A. K. Eckrovskiy and V. G. Filatov [78] (Fig. 26). Specimen/sample 3, being attached in the joints of 1 levers 2, is loaded by the assigned/prescribed bending moment. The pure bending of sample is realize/accomplished on the arc of radius R around the axle/axis of 4 levers.

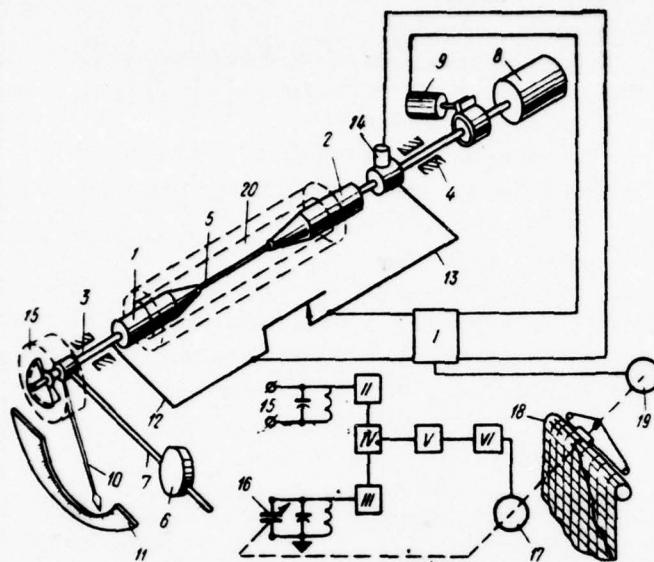


Fig. 27. The installation diagram for measuring stress relaxation in wire during the twisting: 1, 2 - captures; 3, 4 - support; 5 - specimen/sample; 6 - load; 7 - lever with alterrating/variable arm; 8, 9 and 17 - electric motors; 10 - arrow/pointer; 11 - scale; 12 and 13 - closed contact of system; 14 - electromagnetic clamping fixture; 15 - capacitance pickup; 16 - condenser/capacitor; 18 - mechanism of the recording of diagrams; 19 - limiter load; 20 - reheating furnace; I - relay device of load; II-III - high-frequency oscillators; IV - mixer; V - detector; VI - exit relay device.

In one of the levers, is arranged/located measuring cell/element by 5, which is elastic interchangeable arm with the stuck on it two resistance strain gauges. heating specimen/sample is realized/accomplished in furnace, moreover levers heat only on a comparatively low section and additionally they cool by water so that the temperature on measuring arm would remain constant. The loading of specimen/sample is manufactured after its warming up, for which in the shutter valve of furnace are gashes, which make it possible to spread levers in the process of testing.

The study of relaxation of stresses during twisting carries out in different types specimen/samples. Thus, for instance, for relaxation test of voltages in steel wire is designed the setting up, presented schematically in Fig. 27 [41, 20]. the initial stress in specimen/sample on this setting up is assigned by the rotation of load 6, connected with one of the captures. The value of residual stress is recorded automatically with the aid of mechanism by 18, and also we can be controlled with the aid of arrow/pointer by 10. The angle of twist of specimen/sample is supported by constant with the aid of servo system, which abstract/removes the normally open contact of 13 systems, fasten/strengthened to capture without load. Setting up is equipped by the furnace, which makes it possible to carry out the tests of specimen/samples at temperature to 600°C.

Analogous stand of specimen/samples with a diameter of 1-5 by the length of 10-100 mm is described in work [66]. Instrument sensitivity composes 0.2-0.3".

3. Relaxation in coiled springs.

Relaxation tests of full-scale coiled springs are usually the technological tests, which carry out for determining the stability of springs in time. This procedure [79] provides for testing the cylindrical spring, put on to mandrel/mount and compressed to the specific value. Initial stress calculates from the formula

$$\tau_0 = \frac{8Dk}{\pi d^3} \cdot \frac{G_t}{G_0} p_0, \quad (114)$$

where D - a diameter of spring; d - wire diameter; G_0 and G_t - moduli of shear at 20°C and temperature of testing t respectively; k - variation factor of the windings of spring; p_0 - load, applied at room temperature for accomplishing of compression of spring to assigned magnitude $f_0 = h_0 - h_1$ (h_0 and h_1 - height of unloaded spring and at the moment of loading with 20°C respectively).

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The residual stress

$$\tau_r = \tau_0 \frac{h_r - h_1}{f_0}, \quad (115)$$

where h_r — height of the spring, unloaded at the moment of time r ,
with free state.

For measuring the elastic set of spring, are applied the special
attachments with electric feeler, which make it possible to
manufacture measurements with an accuracy to ± 0.01 mm.

It should be noted that during spring testing, just as during
tension tests, loading they manufacture only in elastic region.

For decreasing the intensely developing processes of stress
relaxation directly with their loading in a series of cases is
employed the technological operation, called "compression", that
consists of following. The manufactured spring they compress until
the contact of turns and withstand for a long time in this state. The
process of the compression of springs is considered finished, when
the rate of flow of relaxation processes becomes constant.

For studying the laws governing stress relaxation in compression
springs with their compression, is designed special setting up [41, p
313] (Fig. 28), that makes it possible to carry out tests at room and
elevated temperatures with the automatic recording of relaxation

curves.

Setting up consists of the loading device, furnace, scale and photorelay. Spring 3 installs to support/socket, then through it they put through thrust/rod by 4. Jack 9 serves for lift and lowering of suspension 16, in which are installed weights by 5 and hydro-weight 6, with loading and unloading of spring. When suspension is free/released from jack by 9 and entire/all load is concentrated on spring by 3, the slot of photocell is mounted in the shadow of flag 15, and it is included by photorelay 19. With an incidence/drop in the carrying abilities spring, it is compressed and the flag, fixed to the arrow/pointer of indicator knob/cap 1, open/discloses the slot of photocell, in consequence of which is switched on the relay, closing the circuit of electromagnetic narrowing 8, is open/disclosed siphon by 7 for pumping from hydro-weight 6.

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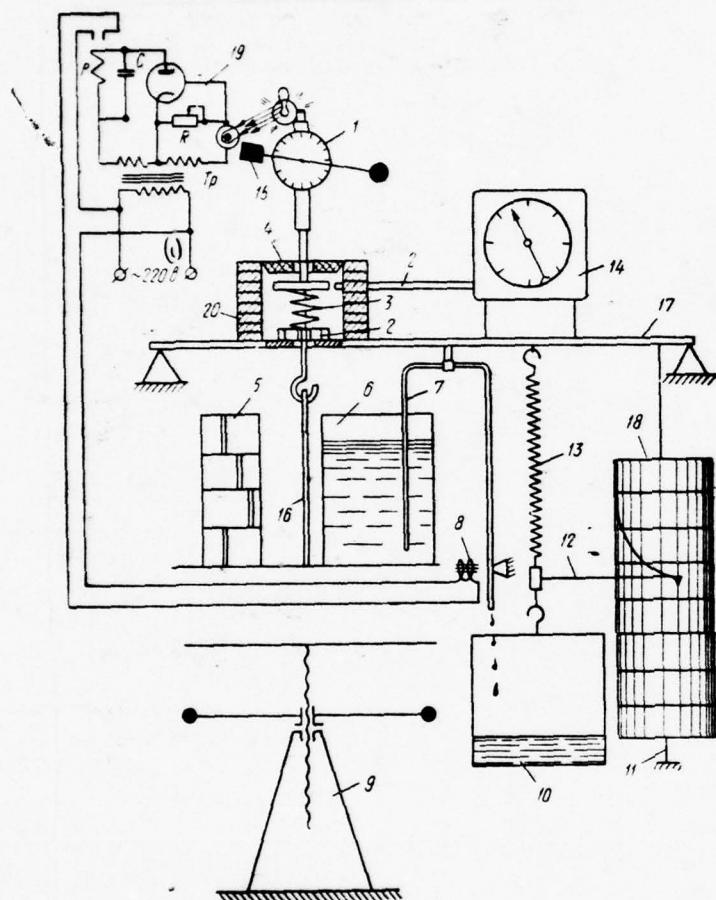


Fig. 28. Diagram of automatic installation for measuring stress relaxation in compression springs: 1 - indicator knob/cap; 2 - thermocouple; 3 - tested spring; 4 - thrust/rod; 5 - weight; 6 - hydro-weight; 7 - rubber tube; 8 - electromagnetic narrowing; 9 - jack; 10 - bucket; 11 - axle/axis of electric clocks; 12 - indicating

and recording arrow/pointers; 13 - weight gage spring; 14 - potentiometer EMD-237; 15 - rifleman/gunner-flag; 16 - cargo suspension; 17 - table cf setting up; 18 - recording drum electric clocks; 19 - photo relay; 20 - electric furnace.

Key: (1). V.

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The evacuated water falls into the bucket of 10 scales 13 and its mass, which corresponds to an incidence/drop in the load of spring in time, is recorded by recording mechanism 18.

In recent years [36, p 239; 80] A. A. Chizhikom is developed the method of relaxation test of the metal of full-scale steam superheating ducts. Tests carry out under cnditions of compression in special spring specimen/samples with the rectangular cross section cf turn (Fig. 29). In ccnnection with the ccnditions of obtaining sufficient accuracy/precision of tests and prevention/warning of loss cf stability for the ducts with a diameters of 25-75 mm are establish/installled optimum dimensions of the spring specimen/sample: length 40, spiral pitch 8 mm. Samples usually manufactures by milling and each specimen/sample is subjected the calibrating, which consists of determination of effort/force, necessary for upsetting of

specimen/sample to the height, which corresponds to the length of bore. As a result of calibrating, is determined the rigidity of specimen/sample $c=P/\delta$, where P - strain; δ - this corresponding effort/force linear defcrmation of specimen/sample.

The initial upsetting of specimen/sample $\Delta\lambda_0$ determines from the formula

$$\Delta\lambda_0 = \frac{k_2}{\sqrt{3}} \cdot \frac{E_{20}}{E_T} \cdot \frac{(2a)^2(2b)}{cR_{cp}} \sigma_{01}, \quad (116)$$

where σ_{01} - conditional initial stress; E_{20} and E_T - module/moduli of elasticity at 20°C and temperature of testing t; $2a$ - width of the section/cut of turn; $2b$ - height; k_2 - constant, which depends on ratio b/a:

b/a . .	1	1,2	1,5	2,0	2,5	3	4	5	10
k_2 . .	0,208	0,219	0,231	0,246	0,258	0,267	0,282	0,294	0,312— 0,333

Conditional initial stress equal to of initial stress annular specimen/sample, calculated according to formula (102).

Equation (116) is derived on the basis of the theory of Kachanov [29], according to which the agreement of the curves of stress relaxation under conditicons of the different stressed states is possible only with the equality of the parameter of relaxation χ , of depending on character stressed state.

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Springs are tested in the special attachments (see Fig. 29). Value $\Delta\lambda_0$ is created by tightening by two back nuts and it is record/fixed with the fixing inserts with a height of $h=H-\Delta\lambda_0$, where H - height of specimen/sample. This method of tests, just as testing with the annular specimen/samples of Oding, is mass; tests on by 15-20 specimen/samples.

4. Relaxation in multistressed state.

By researchers' series are studied the criteria of stress relaxation in multistressed state.

Multistressed state is created by unidirectional tension and twisting of solid and thin-walled tubular specimen/samples. Tests they carry out with room [81] and at the increased [36, p 246; 82; 83] temperatures. However, the conditions of the assignment of stresses and strain in the time on of the utilized for conducting specific tests machines somewhat are distinguished. In one case [81] during testing are supported by constants axial deformation and ratio/relation of principal stresses.

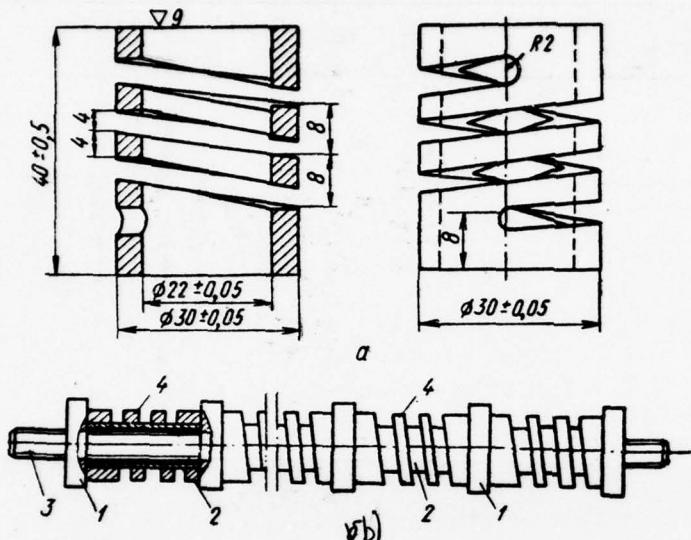


Fig. 29. Specimen/sample (a) and device (b) for the mass tests of steam superheating ducts for creep and stress relaxation: 1 - the back nuts; 2 - fixing inserts; 3 - rod; 4 - specimen/sample.

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In other case [82] constants they will be angle of twist and the ratio/relation of axial force and torsional moment, but axial deformation it remains uncontrollable. In experiments of V. S. Namestnikov [83] and in V. V. Osad'juk [36, p 246] constants are axial elongation, and angle of twist.

The setting up, utilized in work [83], differs from testing machine by creep [84] in terms of the introduction of the special attachments, making it possible to support with constants displacement and elongation. The accuracy/precision of the maintenance of axial defcrmaton is equal to $\pm 0.5-1.0 \cdot 10^{-5}$, and displacement $\pm 0.8-1.7 \cdot 10^{-5}$. A deficiency in the setting up is comparatively long time between the beginning of testing and the end of the load (to 45 s).

The setting up, created in the institute of the problems of the strength of AS UkrSSR [85], possesses some specific special feature/peculiarities: for the continuous measurements of effort/forces in specimen/sample during entire time of tests into the loading circuit of setting up, are introduced rigid liquid the dynamometers, in consequence of which the compliance/pliability of the component/links of the loading circuit is considerably lesser than pliability of specimen/sample. This provides the reproduction of the phenomenon of stress relaxation virtually in pure form; for the elimination of errors during the determination of the stresses in specimen/sample due to the cscillation/vibrations of the temperature in furnace specimen/sample with the loading frame they are placed under identical temperature conditions.

This setting up makes it possible to carry out relaxation tests

of stresses with the stretching forces to 30000 N (3000 kg), the torsional moment to 35 m, with temperatures of up to 900°C.

Figures 30 depicts the schematic of the mechanical feature of the setting up. Specimen/sample 9 by its upper end, which has threaded thread, is attached in cross-beam by 7, which is connected with upper turntable by 13 by means of lateral thrust by 10. Under lower plate/slab 15, is placed liquid dynamometer of the system of the loading of specimen/sample by axial force. In the assembly of dynamometric device, they enter housing 2 whose working volume is completely filled by liquid 3 and by insert/bushing of temperature compensator 17, diaphragm/membrane 16 (foil with a thickness of 0.1 mm), pressing flanges 5, packing 4 and specimen manometer 18. The butt end of the specimen/sample is fastened to central thrust/rod by 11, connected with the assembly of loading (worm reducer 1).

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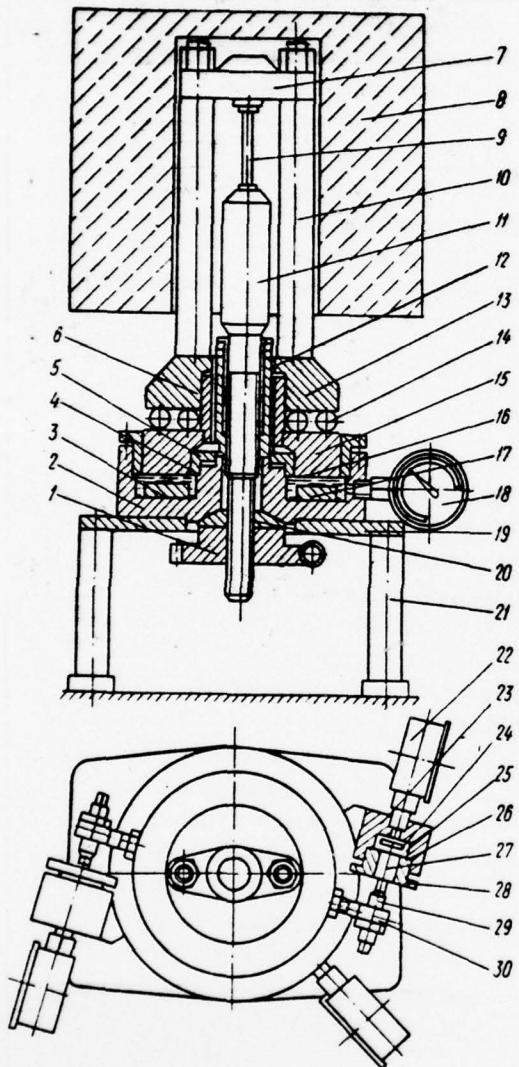


Fig. 30. Stand for relaxation in multistressed state.

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The elimination of the bending stresses in specimen/sample is provided by spherical block/backing 20 and by possibility of the displacement of upper end of the specimen/sample because of the clearances between the lower plate/slab and pressing flanges. During the rotation/revolution of the wheel of 1 wcrm reducer, the specimen/sample is loaded by the axial force, determined by manometer.

For creation and measurement of that twisting, the specimen/sample of torque/moment is two identical device each of which consists of finger/pin by 30, attached of upper turntable, screw/propeller 29, pusher 27 and liquid dynamometer of the system of the loading of specimen/sample by the torsional moment. In the assembly of dynamometric device, enter pressing flange 28, membrane 25, packing 26, working fluid 24 with the temperature compensator, housing 23 and specimen manometer 22. The housing of dynamometer is connected with fixed base by 19, arranged/located on struts 21. During the rotation/revolution of screw/propeller, upper turntable together with lateral thrust, cross-beam and upper end of the specimen/sample is rotated on ball bearing by 14, being centered on the guide 6. In this case, the central thrust/rod with the attached in it butt end of the specimen/sample remains immobile since the lower end/face of nut

12 is forced against housing by 2. The value of the torque/moment, of twisting specimen/sample, is determined from readings of manometer.

For heating of specimen/sample under conditions of high temperatures, serves the resistance furnace to 8, into which are placed central thrust/rod with specimen/sample and loading frame. For the control of the deformations of specimen/sample in the direction of the action of its effort/force and torsional moment, there are special devices.

After the loading of specimen/sample by axial force and torsional moment it occurs relaxation of axial and tangential stresses, in consequence of which are decreased readings of the corresponding manometers. With respect to changes in these readings, are constructed relaxation curves with the aid of calibration graphs.

The accuracy/precision of the maintenance of axial deformation comprised $\pm 2.8 \cdot 10^{-5}$, and shearing strain $\pm 1.3 \cdot 10^{-3}$ rad.

For tests apply solid specimen/samples with a diameter of 7 and tubular by diameter 10x1 mm.

The study of the effect of the complex stressed state on the course of the processes of relaxation will make it possible to reveal/detect/expose the special feature/peculiarities of the behavior of materials under these conditions.

By V. S. Namestnikov in work [83] is conducted the assumption that during relaxation tests occurs the elastic incompressibility of the material of the twisted and elongated tube. Then in the case of the proportionality of the deviator of the relaxing tangential τ and axial σ stresses to the deviator of initial stresses must be observed the relationship/ratio

$$\frac{\tau}{\sigma} = \frac{\tau^0}{\sigma^0} = \lambda = \text{const.} \quad (117)$$

The validity of relationship/ratio (117) checks in specimen/samples made of duralumin of D16T and copper with 150°C [83] with two repeated loadings. The duration of experiments is varied from 1 to 56 h (Table 7).

The values of intensity σ_i calculate according to the formula

$$\sigma_i = \sqrt{\sigma^2 + 3\tau^2}. \quad (118)$$

From the graphs of a change in value λ during the tests of different specimen/samples, is evident certain decrease λ in the course of time. However, on the completion of the first stage of the

accelerated relaxation of value λ , they are stabilized.

Given in Table 7 maximum deviations $\lambda(\tau)$ from λ during loading show that, with exception of four tests, value $\Delta\lambda/\lambda$ does not exceed 140/0.

V. S. Osasyuk [86] conducts research in solid specimen/samples made of heat-resistant austenitic steels of Kh15N35VT and Kh18N10T with 650°C. in this case, are varied the values of the initial axial σ_x^0 and tangential τ_{xy}^0 stresses and relationship/ratio τ_{xy}^0/σ_x^0 — within limits from 0 to 1.

The results of the tests of steel of Kh15N35VT Fig. 31 depicts in the form of the dependences of an incidence/drop in longitudinal stresses $\Delta\sigma_x$ from initial tangential stresses τ_{xy}^0 for the different values of relaxation time.

Figure 31 shows that the dependences indicated have linear character to values τ_{xy}^0 , at which maximum principal stress in the skins of specimen/samples reaches the yield point of material. On the basis of the experiments conducted is proposed the dependence of an incidence/drop in longitudinal stresses in the complex stressed state from an incidence/drop in longitudinal stresses in uniaxial stressed state ($\Delta\sigma_x$):

$$\Delta\sigma_x = \Delta\sigma_{x_1} \left(1 + \frac{\tau_{xy}^0}{\sigma_x^0} \right). \quad (119)$$

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Table 7. Stress relaxation in multistressed state.

(1) Material	(2) Number of specimen sample	σ (3) MN/m^2	τ (4) kg/mm^2	σ_L (3) MN/m^2	τ_L (4) kg/mm^2	λ	$\Delta\lambda/\lambda, \%$	(5)		
(6) First loading										
Д16Т	4	201,5	20,15	58,5	5,85	225,6	22,56	0,29	-14	23
	6	199	19,9	89,8	8,98	252,6	25,26	0,452	+4	21
	10	96,6	9,66	24,9	2,49	105,8	10,58	0,258	-25	19
	12	259	25,90	63,4	6,34	281,4	28,14	0,242	-16,7	24
	16	62,3	6,23	100,5	10,05	187,3	18,73	1,45	-4,1	28
	244	211,5	21,15	115,7	11,57	291,4	29,14	0,55	-9	24
	1Н	150,6	15,06	84,2	8,42	209,8	20,98	0,56	-10,7	4,5
	2Н	226	22,6	125,3	12,53	313,4	31,34	0,555	-4	8,5
	2Н	275,6	27,56	136,5	13,65	363,1	36,31	0,496	-7	24
	1Н	198,7	19,87	110,0	11,0	275,2	27,52	0,558	-10	32
	3Н	232,6	23,26	135	13,5	329,9	32,99	0,58	-14	28
(7) Медь	16	65,6	6,56	69	6,9	138	13,8	1,05	-0,2	1
	18	101	10,1	72,8	7,28	162	16,2	0,72	-1,0	1
	20	104	10,4	80	8,0	173	17,3	0,77	-9,7	21
	22	51	5,1	42,3	4,23	89,3	8,93	0,83	-15,7	23
	1Р	77,7	7,77	58,2	5,82	127,3	12,73	0,74	-12	22
	2Р	44,8	4,48	28,3	2,83	63	6,3	0,587	-24	17
	3Р	90	9,0	39,3	3,93	112,8	11,28	0,437	-9,1	0,75
(8) Second loading										
(7) Медь	4	230	23,00	64,1	6,41	255,3	25,53	0,28	-12,5	33
	6	218	21,80	103,7	10,37	282,5	28,25	0,477	-5,0	20
	12	301,6	30,16	64,7	6,47	321,7	32,17	0,214	-14	14
	16	76	7,6	109	10,9	103,7	10,37	1,44	-3,5	23
	20	108,5	10,85	81,8	8,18	178,3	17,83	0,75	-5	28
	22	75	7,50	58	5,8	125,4	12,54	0,77	-6,5	13
									-	-

Key: (1) - Material. (2) - Number of specimen/sample. (3) - MN/m^2 . (4) - kg/mm^2 .

(5) - h. (6) - First loading. (7) - Copper. (8) - Second loading.

The disagreement between the experimental and calculated by formula (119) values does not exceed 40/o, but computed values $\Delta\sigma_x$, found from the relationship/ratios, instituted on IV theories of strength, will render/stow in a number of cases considerably less than experimental ones (to 160/o).

V. V. Osadyuk [85] gives also relaxation tests of tubular samples made of steel of Kh15N35VT. It is establishinstalled, that between reduction in the intensity of stresses $\Delta\sigma_{it}$ and initial intensity of loading σ_{i0} there is a linear dependence (Fig. 32). However, the points, which correspond to twisting and elongation with twisting, are furnished somewhat higher than the points, corresponding to unidirectional tension.

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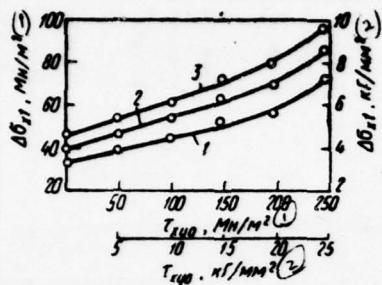


Fig. 31. The dependence of an incidence/drop in longitudinal stresses $\Delta\sigma_{zt}$ in specimen/samples made of the alloy of Kh15N35VT (EI612) from initial tangential stress τ_{xy} through the different time intervals, h : 1 - 50; 2 - 100; 3 - 250.

Key: (1) - MN/mm². (2) - kg/mm².

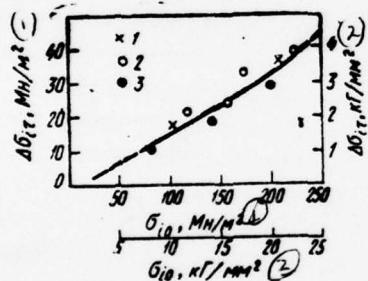


Fig. 32. Graph/diagram of dependence $\Delta\sigma_{zt} - \sigma_{z0}$: 1 - twisting; 2 - elongation with twisting; 3 - unidirectional tension.

Key: (1) - MN/mm². (2) - kg/mm².

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CHAPTER IV.

Effect of different factors on the process of relaxation of stresses and its criteria.

The factors, which affect the course of the process of stress relaxation, it is possible to divide into internal ones - depending on tested material and external - from it those not depending.

A number of internal factors includes:

the chemical composition of alloy; the structure: mark/brand and microstructure, fine/thin (mosaic and dislocation) structure; the technological special feature/peculiarities: the method of melting, working by pressure, work hardening, heat treatment.

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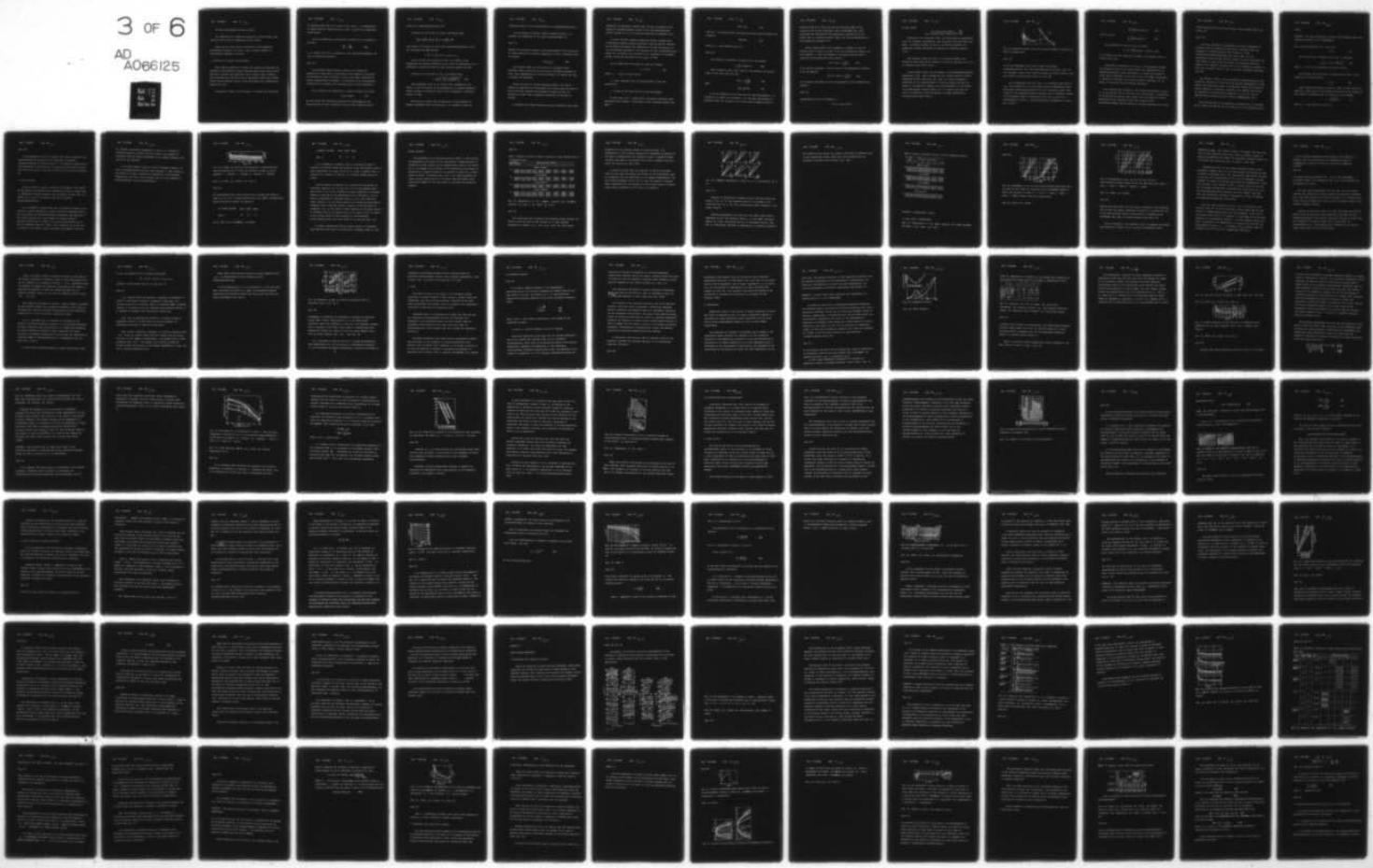
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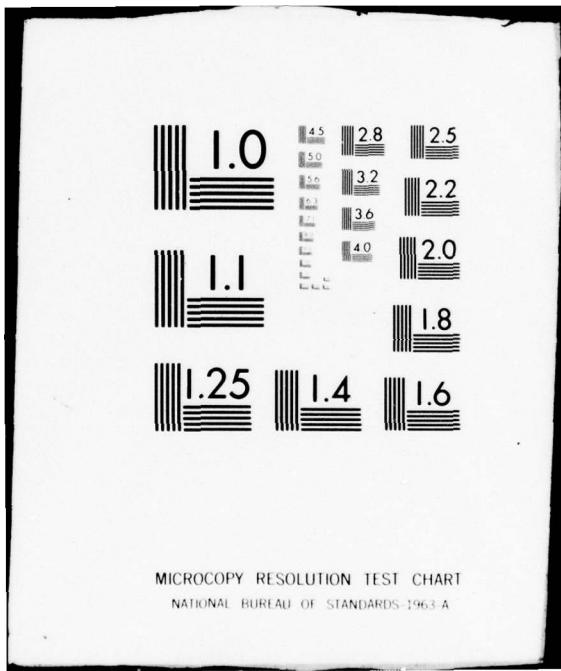
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The main environmental factors include:

the conditions of loading and unloading; initial stress; time (service life of part); temperature; scale factor.

Below are set forth data on the effect of the enumerated environmental factors; the role of basic internal factors is illuminated in Chapter VI and VII.

1. Conditions of loading and unloading.

Ideal stress relaxation is called the process of decreasing the stresses in the instantly loaded specimen/sample which during entire testing is located into absolutely rigid attached state. However, such conditions are virtually almost impossible, since real systems cannot ensure absolute rigidity (pure relaxation) and instantaneous loading [89, 90].

In Chapter II effect of the rigidity of loading was considered

in equations with the aid of factor $1+cE$, where c - an adaptability of system (elastic component/link), equal to zero for an absolutely rigid system.

From the differential equation of relaxation for the theory of the flow

$$\frac{d\sigma}{d\tau} = -\frac{E\dot{\epsilon}_n}{1+cE} \quad (120)$$

it is evident that with an increase in the compliance/pliability the rate of relaxation descends.

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In absolutely pliable system ($\sigma=\text{const}$) are created the conditions of pure creep. In absolutely rigid system are developed the processes of pure relaxation. On test data under conditions of certain adaptability of system, it is possible by the corresponding calculations to determine the characteristics of pure relaxation.

After accepting the similarity of curves of creep in the form

$$\dot{\epsilon}_n(\sigma, \tau) = \Omega_1(\tau) \sigma^m, \quad (121)$$

we will obtain the following expressions for determining of the characteristics of pure relaxation from the data, obtained during

tests with compliance/pliability $c \neq 0$.

According to the theory of aging, accordingly [48],

$$\frac{1-\rho}{\rho^m} = \frac{1-\rho_c}{\rho_c} (1+cE) \text{ or } \frac{\Delta\sigma}{\sigma^m} = (1+cE) \frac{\Delta\sigma_c}{\sigma_c^m}, \quad (122)$$

where index c is related to tests with compliance/pliability c and are introduced the designations

$$\rho = \frac{\sigma}{\sigma_0}; \quad \rho_c = \frac{\sigma_c}{\sigma_0}; \quad \Delta\sigma = \sigma_0 - \sigma; \quad \Delta\sigma_c = \sigma_0 - \sigma_c.$$

As can be seen from expression (122), the effect of the adaptability of system, according to the theory of evaporation, it is developed to identical degree for the different moments of time.

According to the theory of flow, accordingly [70],

$$\sigma = \frac{\sigma_c}{1+cE} \left[\frac{1+cE + (m-1)E\Omega_1(\tau)\sigma_0^{m-1}}{1+(m-1)E\Omega_1(\tau)\sigma_0^{m-1}} \right]^{m-1}. \quad (123)$$

From expression (123) it is evident that, according to the theory of flow, the effect of the adaptability of system differently affects results of relaxation tests, which correspond to different moments of time.

When from any reasons the determination of the rigidity of loading represents known difficulties, it is possible to use the

following method of value determination of compliance/pliability c.

In the process of testing, besides residual stress σ_0 , is measured the elongation of the loaded specimen/sample Δl .

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Knowing its calculated length L and module/modulus of the elasticity of tested material at operating temperature, value c calculates from the formula

$$c = \frac{\Delta l}{L} \cdot \frac{1}{\sigma_0 - \sigma_e}. \quad (124)$$

The definite effect on the results of relaxation tests, especially under conditions of the rapidly developing processes of creep (high temperatures and initial stresses), is exerted the rate of loading and unloading.

During the tests of annular specimen/samples, the rate of loading is connected with the heating rate; during tests for bend of plates virtually possible instantaneous loading. The rate of unloading in these cases completely corresponds to the rate of process.

As concerns the loading conditions during relaxation tests under

conditions of elongation, usually they utilize two methods of the loading of specimen/samples; either to the assigned/prescribed initial voltage σ_0 or to the assigned magnitude of elongation Δl_0 .

In work [39] were compared relaxation curves, obtained with instantaneous loading (ideal relaxation), with the curves, obtained by two methods indicated. The comparison of curves was carried out via calculations according to the theories of flow, strengthening and aging. Let us conduct as an example of the comparison of relaxation curves, calculated according to the theory of flow.

Let us assume that the curves of creep are similar:

$$\dot{\varepsilon}_n = B_1(\tau) f(\sigma), \quad (125)$$

where $\dot{\varepsilon}_n$ - a rate of creep strain;

τ - time, calculated off the torque/moment of the load application;

σ - stress in the cross section of specimen/sample.

In this case, $B_1(\tau)$ - monotonically decreasing function, which approaches with increase τ the positive limit, moreover already with small τ .

$$B_1(\tau) \leq B_1(0), \quad (126)$$

and $f(\sigma)$ - the monotonically increasing function, which satisfies the condition

$$f(\sigma) > A\sigma^p, \quad (127)$$

where A, p - some constants and $p > 1$.

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The process of relaxation is described by the equation

$$\frac{1}{E} \cdot \frac{d\sigma}{d\tau} + B_1(\tau) f(\sigma) = 0. \quad (128)$$

Ideal relaxation (Fig. 33a, curve 1). The solution of equation (128) in this case takes the form

$$\Omega_1(\tau) = -\frac{1}{E} \int_{\sigma_0}^{\sigma} \frac{d\sigma}{f(\sigma)}, \quad (129)$$

where

$$\Omega_1(\tau) = \int_0^{\tau} B_1(\tau') d\tau'. \quad (130)$$

It is not difficult to see that with any fixed recorded τ an increase in σ_0 leads to an increase σ . At the same time because of condition (127) the integral in the right side of equation (129) is

converged when $\sigma_0 \rightarrow \infty$. Hence follows the existence upper of the limiting curve of the relaxation, which corresponds $\sigma_0 = \infty$. This conclusion was confirmed by the experiments, carried out by the author with σ_0 , exceeding elastic limit, and also by experiences in the Kennedys and Douglas [57].

Steady loading before the achievement of stress σ_0 . Let the loading occur on curve 4 of Fig. 33 and its durations to stress σ_0 it will comprise τ_1 . Then the process of relaxation for the case in question can be described by the equation

$$\Omega_1(\tau) - \Omega_1(\tau_1) = -\frac{1}{E} \int_{\sigma_0}^{\sigma} \frac{d\sigma}{f(\sigma)}, \quad (131)$$

if we conduct countdown τ from the time of the beginning of loading, or by the equation

$$\Omega_1(\tau + \tau_1) - \Omega_1(\tau_1) = -\frac{1}{E} \int_{\sigma_0}^{\sigma} \frac{d\sigma}{f(\sigma)}, \quad (132)$$

if we conduct countdown from the torque/moment of the termination of loading.

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Set/assuming in view of smallness τ_1

$$\Omega_1(\tau + \tau_1) - \Omega_1(\tau) = B_1(\tau) \tau_1,$$

we will obtain

$$\Omega_1(\tau) - \Omega_1(\tau_1) = \Omega_1(\tau) - B_1(0)\tau_1, \quad (133)$$

$$\Omega_1(\tau + \tau_1) - \Omega_1(\tau_1) = \Omega_1(\tau) - [B_1(0) - B_1(\tau)]\tau_1. \quad (134)$$

According to the condition (126), the right sides of expressions (133) and (134) and, consequently, also equations (131) and (132) with small τ virtually coincide. We will be restricted therefore to examination curved, determined by simpler for structure equation (131).

From equation (129) and (131) it is directly evident that relaxation curve with steady loading to stress σ_0 (see Fig. 33, 2) it is furnished above ideal curve 1.

Steady loading before the achievement of the assigned/prescribed deformation $\varepsilon_0 = \frac{\sigma_0}{E}$. Let us assume that the loading occurs as before lengthwise curved 4 (see Fig. 33), since the rate of loading is determined by the characteristics of testing machine and does not depend on the method of loading. Up to torque/moment τ_2 , the stress in specimen/sample reaches values σ^* . It is easy to see that the curve of relaxation 3 with the method of loading indicated is arranged/located below curve 2.

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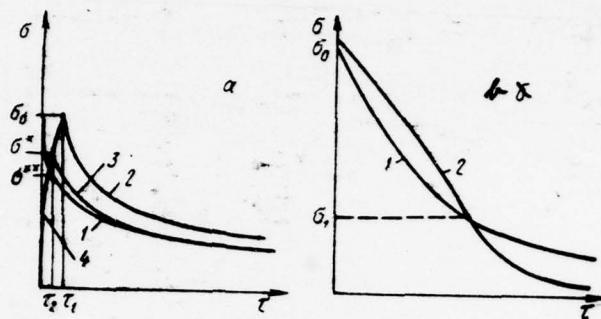


Fig. 33. Relaxation curves with the different methods of loading (a) and of unloading (b).

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In initial relaxation time, this follows from obvious relationship/ratios $\tau_2 < \tau_1$ and $\sigma^* < \sigma_0$; subsequently curves 2 and 3 do not intersect, since at the identical values σ of point curved 2 they have smaller in the absolute value of value $\frac{d\sigma}{d\tau}$.

Let us demonstrate now that curve 3 is furnished above curve 1, i.e., that loading up to the assigned/prescribed deformation gives better/best approach/approximation to ideal relaxation curve, than loading to the assigned/prescribed voltage. Let us designate through σ^{**} the ordinate ideal of relaxation curve with τ_2 . Up to the torque/moment of time τ_2 , full/total/complete deformation is equal: for a curve 1

$$\frac{\sigma^{**}}{E} + \int_0^{\tau_i} B_1(\tau) f[\sigma_1(\tau)] d\tau = \varepsilon_0 \quad (135)$$

and for curve 2

$$\frac{\sigma^*}{E} + \int_0^{\tau_i} B_1(\tau) f[\sigma_2(\tau)] d\tau = \varepsilon_0. \quad (136)$$

From expressions (135) and (136) we obtain

$$\sigma^* - \sigma^{**} = E \int_0^{\tau_i} B_1(\tau) \{f[\sigma_1(\tau)] - f[\sigma_2(\tau)]\} d\tau. \quad (137)$$

It is obvious, at zero times $\sigma_1(\tau) > \sigma_2(\tau)$. Thus, from equation (137) it follows that $\sigma^* > \sigma^{**}$.

Calculations according to the theory of strengthening showed, that relaxation curve with loading before the achievement of the assigned/prescribed initial deformation is formed by the shift of curved ideal relaxation to the right to very low value, which makes it possible to consider both curves virtually coinciding. In the theory of aging both curves coincide completely.

From calculations according to the different theories of creep, it is also evident that in the case when creep strain ε_m , accumulated in the process of loading, they compare with the amount of elastic deformation, then relaxation curve with loading to the assigned/prescribed initial voltage σ_0 actually coincides with curved

ideal relaxation for the initial stress, which exceeds value σ_0 by value $\varepsilon_n E$.

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The data, obtained in experimental work [91], confirmed for different rates of loading the made above conclusion about the agreement of relaxation curves with loading up to the assigned/prescribed deformation with ideal curve. At high temperatures and with high initial stresses, to which correspond the high values of creep rates, the results of relaxation tests can depend on the maximally attained rate of the unloading of machine, if this rate is smaller than the rate of process. Aforesaid illustrates Fig. 33b.

For period of time r_1 , the spontaneously passing process of the relaxation (see curve 1) will cause the smaller accumulation of creep strain, than when creep strain is accumulated during the decrease of load at velocity of unloading, attained by the machine (see curved 2). Therefore the condition of relaxation $\varepsilon_0 = \varepsilon_n + \frac{\sigma}{E} = \text{const}$ will be observed during testing only with certain torque/moment $r_2 > r_1$.

The required rate of the unloading of machine can be calculated. Let us conduct calculation for the conditions of the constant rate of

creep¹.

FOOTNOTE 1. At high temperatures the rapid creep usually occurs with constant velocity [27, 47]. ENDFOOTNOTE.

Let us accept expression for a creep rate

$$\dot{\epsilon}_n = A\sigma^n. \quad (138)$$

Then creep strain, accumulated for time τ_1 , comprises

$$\epsilon_n = \int_0^{\tau_1} A(\sigma_0 - \alpha\tau)^n d\tau = \frac{A\sigma_0^{n+1}(1 - \rho^{n+1})}{(n+1)\alpha}, \quad (139)$$

where α - a rate of the unloading of machine; $\rho = \sigma/\sigma_0$.

At the same time creep strain, accumulated for time τ_1 under conditions of pure relaxation,

$$\epsilon_n = \frac{\sigma_0 - \sigma}{E}. \quad (140)$$

After equating expressions (139) and (140), we will obtain the condition, which connects the minimally necessary for the passage of the process of relaxation rate of unloading in the machine:

$$\alpha = \frac{(1 - \rho^{n+1}) E \dot{\epsilon}_{n\sigma_0}}{(1 - \rho^n)(n+1)}, \quad (141)$$

where $\dot{\epsilon}_{n\sigma_0}$ - creep rate with stress σ_0 .

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From expression (141) it is evident that value α depends on the characteristics of material at the temperature of testing (slope/inclination of curves of creep n , the modulus of elasticity at the temperature of testing E and of creep rate with initial stress), and also on the value of the step of stress with the first unloading $\Delta\sigma$.

2. Initial stress.

Initial stress σ_0 exerts a substantial influence on the course of the process of relaxation and, consequently, also on stress level σ_r , "remaining" through different time intervals. In this case, the effect σ_0 in I and II relaxation times has its special feature/peculiarities.

It is customary to assume that with an increase in value σ_0 the process of stress relaxation in initial period is intensified and is more noticeable, the higher homologous temperature. The analysis of the initial sections of a large number of primary curves of relaxation shows that the effect of initial stress affects not so much the absolute value of a drop in the voltage $\Delta\sigma$, as on the rate of descent in the stress, which is evident, for example, from Fig.

34. However, the mutual arrangement of curves $\sigma - \tau$, obtained at different values σ_0 , during the first stage of the process of relaxation does not always correspond to the initial stresses, with which they are obtained.

if we assign certain value $\Delta\sigma$, then at different values σ_0 it will be reached through different time intervals τ . Than higher σ_0 , the shorter the time, necessary for achievement of the assigned magnitude $\Delta\sigma$, and vice versa, although here it is not possible to establish/install strict proportionality.

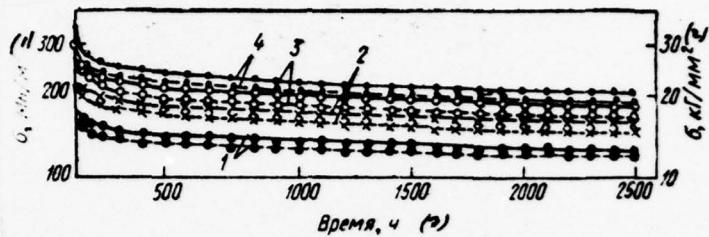


Fig. 34. Primary the curves of the relaxation cf heat-resistant nickel-chrcmum alloy at 750°C and different values σ_0 , Mn/mm^2 (kg/mm^2): 1 - 200 (20); 2 - 250 (25); 3 - 300 (30); 4 - 400 (40).

Key: (1). Mn/mm^2 . (2). kg/mm^2 . (3). Time, h.

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The experimental data, which confirm this position, are given in Table 8. E.g., for a nickel-chrcmum alloy with 600°C a voltage drop across 50 Mn/mm^2 ($5 kg/mm^2$) is reached at

σ_0 , Mn/mm^2 (kg/mm^2)	100 (10)	150 (15)	200 (20)
--------------------------------------	----------	----------	----------

time, h	200	60	15
---------	-----	----	----

and at 750°C for $\Delta\sigma=100$ Mn/mm^2 (10 kg/mm^2):

σ_0 , MN/m² (kg/mm²) 200 (20) 250 (25) 300 (30)

time, h.	200	30	15
----------	-----	----	----

It is necessary to emphasize that in the given in table 8 examples the initial stress was knowingly lower than elastic limit at this temperature. At higher values of σ_0 , close to elastic limit or exceeding it, kinetics of drop in σ_0 can sharply differ from that shown.

Another picture is observed in II period when the process of relaxation continues with by the more or less free-running speed. Here effect of σ_0 on the intensity of stress relaxation is virtually absent, in any case at the temperatures lower than 0.5 T_{nn} . Of the rates of relaxation at different values σ_0 , as a rule, were very close. Curves $\sigma-r$ on the second section are similar and equidistant, differing only in relative position relative to the axle/axis of ordinates, i.e., in the level of those remaining at the given instant of stresses. This is illustrated well by the given to Fig. 34 family of the primary curves of the relaxation of heat-resistant nickel-chromium alloy with four values of σ_0 (see also Fig. 111).

At higher temperatures ($>0.5 T_{nn}$) primary curves $\sigma-r$ frequently lose similarity and rates of relaxation at different values σ_0 they

become variable.

The dependence of the remaining (final) stress σ_t from initial is determined by the effect of the last/latter on course process of relaxation in both periods. At the temperatures, which do not exceed $0.5 T_{mz}$, the degree of an increase of the intensity of the process of relaxation in I period because of an increase in value of σ_0 (within limits to $0.8 \cdot \sigma_{0,2}$) is usually such, that in the final analysis, the higher initial stress leads to the higher remaining stress. This confirm data (Table 9) for four steels of pearlitic and austenitic classes.

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Table 8. Effect of initial stress on kinetics of the voltage drop in 1 relaxation time.

(1) Темпера- тура, °C	(2) σ_0 , MN/m ² , (kg/mm ²)	(3) $\Delta\sigma$, MN/m ² (kg/mm ²), за время, ч							
		1	3	7	15	30	60	120	200
(4) Сталь X15H25B4T									
650	200 (20)	13 (1.3)	16 (1.6)	17 (1.7)	17 (1.7)	19 (1.9)	22 (2.2)	24 (2.4)	25 (2.5)
	250 (25)	24 (2.4)	25 (2.5)	26 (2.6)	28 (2.8)	28 (2.8)	31 (3.1)	32 (3.2)	32 (3.2)
	300 (30)	25 (2.5)	28 (2.8)	30 (3.0)	35 (3.5)	39 (3.9)	42 (4.2)	45 (4.5)	45 (4.5)
(5) Сталь X20H60									
600	100 (10)	15 (1.5)	20 (2.0)	22 (2.2)	25 (2.5)	30 (3.0)	36 (3.6)	42 (4.2)	47 (4.7)
	150 (15)	15 (1.5)	20 (2.0)	30 (3.0)	38 (3.8)	42 (4.2)	50 (5.0)	57 (5.7)	67 (6.7)
	200 (20)	20 (2.5)	40 (4.0)	45 (4.5)	51 (5.1)	58 (5.8)	65 (6.5)	76 (7.6)	87 (8.7)
(5) Сталь XH77TЮ									
750	200 (20)	35 (3.5)	50 (5.0)	55 (5.5)	61 (6.1)	69 (6.9)	80 (8.0)	93 (9.3)	104 (10.4)
	250 (25)	57 (5.7)	65 (6.5)	75 (7.5)	82 (8.2)	97 (9.7)	109 (10.9)	123 (12.3)	138 (13.8)
	300 (30)	57 (5.7)	73 (7.3)	88 (8.8)	100 (10.0)	111 (11.1)	125 (12.5)	141 (14.1)	156 (15.6)
(5) Сталь XH65BMTЮ									
750	200 (20)	8 (0.8)	27 (2.7)	31 (3.1)	38 (3.8)	42 (4.2)	48 (4.8)	53 (5.3)	58 (5.8)
	250 (25)	11 (1.1)	31 (3.1)	37 (3.7)	40 (4.0)	43 (4.3)	50 (5.0)	56 (5.6)	62 (6.2)
	300 (30)	13 (1.3)	37 (3.7)	43 (4.3)	47 (4.7)	53 (5.3)	62 (6.2)	70 (7.0)	83 (8.3)
	350 (35)	15 (1.5)	46 (4.6)	52 (5.2)	58 (5.8)	66 (6.6)	75 (7.5)	86 (8.6)	98 (9.8)

Key: (1). Temperature, °C. (2). σ_0 MN/m², (kg/mm²). (3). $\Delta\sigma$, MN/m² (kg/mm²), for time, h. (4). Steel. (5). Alloy.

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The interconnection of initial and remaining (ring) stresses (or initial stress and drop in the voltage $\Delta\sigma$) is most visually represented by graphs $\sigma_0 - \sigma_t$ and $\sigma_0 - \Delta\sigma$ (Fig. 35). Such curves

construct for the variable values of relaxation time τ (or temperature t). With $t=\text{const}$, $\tau \neq \text{const}$ this dependence is depicted as the beam of hyperparallels for different values τ , passing through the zero point axes of coordinates (Fig. 35a). A similar form has a family of curves $\sigma_0 - \Delta\sigma$ (Fig. 35b).

It should be noted that the beginning of pencil of straight lines at zero point eliminates the concept of the "conditional limit of relaxation" and the possibility of its graphic determination. Are more correct diagrams in Fig. 35c, d, where the pencil of straight lines intersects with the axle/axis of the initial stress at certain point, which corresponds to the limit of relaxation.

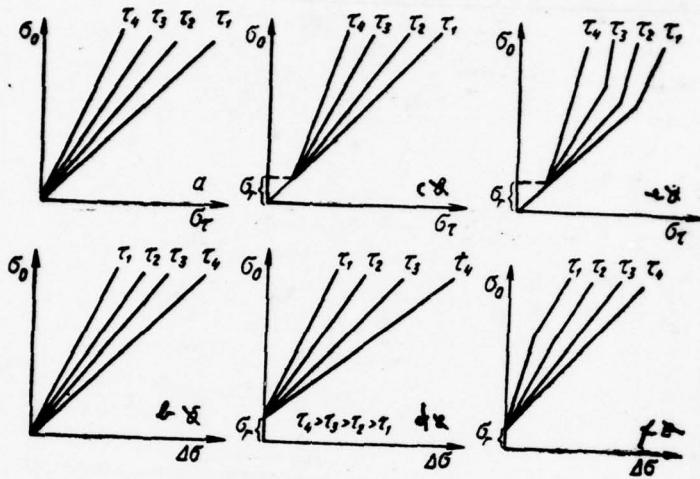


Fig. 35. Schematic dependences $\sigma_\tau = f(\sigma_0)$ (a, c, e) and $\Delta\sigma = f(\sigma_0)$ (b, d, f).

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Examples of dependences $\sigma_\tau = f(\sigma_0)$ and $\Delta\sigma = f(\sigma_0)$ for real alloys are given in Fig. 36, 37. Few analogous graphs it is brought in the literature [65; 92, p. 87], but, unfortunately their treatment is not always correct.

Numerous experimental data show that the lines, which reflect dependence $\sigma_\tau = f(\sigma_0)$, for different values τ , in the common coordinate system, as a rule, curvilinear [94] as to dependence $\Delta\sigma = f(\sigma_0)$ (Fig. 39e, f). Rectilinear character of dependence $\sigma_0 - \sigma_\tau$ during a change of

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the relaxation time within the limits of 500-2000 h is observed only in pure oxygen-free copper, ARMCO iron and in alloys with the structure of uniform solid solution (Fig. 36a).

Table 9. Effect of initial stress σ_0 on the remaining stress σ_t

(1)	σ_0 , MN/m^2 (kG/mm^2)	(2) σ_t , MN/m^2 (kG/mm^2), за время, ч				
		500	1000	2000	3000	10 000*
Сталь 25Х2М1Ф						
550	250 (25) 300 (30) 350 (35) 400 (40)	130 (13.0) 160 (16.0) 177 (17.7) 200 (20.0)	120 (12.0) 145 (14.5) 160 (16.0) 180 (18.0)	105 (10.5) 125 (12.5) 140 (14.0) 160 (16.0)	100 (10.0) 110 (11.0) 125 (12.5) 150 (15.0)	67 (6.7) 70 (7.0) 75 (7.5) 90 (9.0)
Сталь 20Х3МВФ						
550	150 (15) 200 (20) 250 (25) 300 (30)	87 (8.7) 113 (11.3) 137 (13.7) 162 (16.2)	80 (8.0) 106 (10.6) 129 (12.9) 151 (15.1)	71 (7.1) 97 (9.7) 120 (12.0) 140 (14.0)	67 (6.7) 90 (9.0) 110 (11.0) 129 (12.9)	45 (4.5) 54 (5.4) 74 (7.4) 87 (8.7)
Сталь Х15Н35ВМТ						
650	150 (15) 200 (20) 250 (25)	117 (11.7) 154 (15.4) 185 (18.5)	112 (11.2) 143 (14.3) 173 (17.3)	107 (10.7) 133 (13.3) 166 (16.6)	104 (10.4) 130 (13.0) 160 (16.0)	94 (9.4) 120 (12.0) 140 (14.0)
(5) Сплав ХН77ТЮ						
600	150 (15) 200 (20) 250 (25)	115 (11.5) 148 (14.8) 183 (18.3)	106 (10.6) 140 (14.0) 160 (16.0)	100 (10.0) 137 (13.7) 160 (16.0)	82 (8.2)** 107 (10.7)** 135 (13.5)**	58 (5.8) 73 (7.3) 100 (10.0)

FOOTNOTE 1. Extrapolated values.

2. After 5000 h. ENDFOOTNOTE.

Key: (1). Temperature, °C. (2). MN/m^2 (kg/mm^2). (3). MN/m^2 (kg/mm^2).
for time, h. (4). Steel. (5). Alloy.

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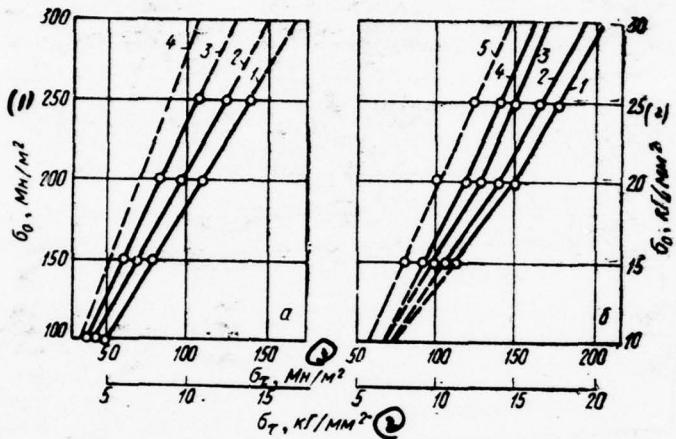


Fig. 36. Dependence $\sigma_t = f(\sigma_0)$: a) iron-nickel-chromium alloy with 20% Cr, 58% Ni with 600°C; b) austenitic steel Kh15N35VMT (EI692) at 650°C. The duration of tests, h: 1 - 500; 2 - 1000; 3 - 3000; 4 - 5000; 5 - 10000. Dotted curves are extrapolated.

Key: (1). MN/m². (2). kg/mm².

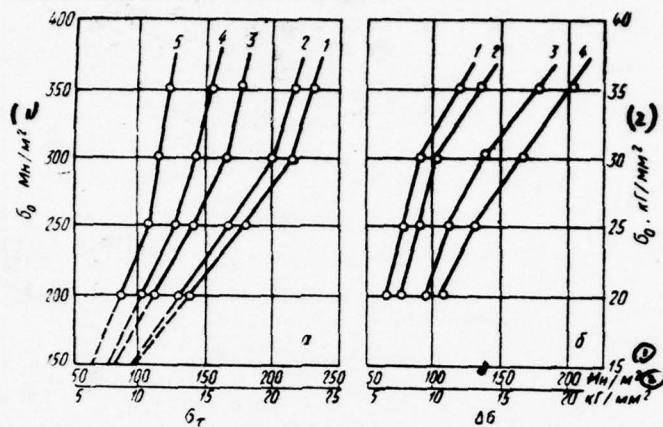


Fig. 37. Dependences $\sigma_t = f(\sigma_0)$ (a) and $\Delta\sigma = f(\sigma_0)$ (b) for a heat-resistant nickel-chromium alloy. The duration of the tests: 1 - 500; 2 - 1000; 3 - 5000; 4 - 10,000; 5 - 20,000.

Key: (1). MN/mm². (2). kg/mm².

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Another form take curves for the alloys, subjected to age hardening, that confirm the graphs, constructed according to the data [93, 94] of the very endurance tests of heat-resistant austenitic steel Kh15N35VMT (Fig. 36b) and nickel-chromium alloy (Fig. 37).

With an increase in the relaxation time, is observed the gradual straightening of curves. But if for steel Kh15N35VMT at 650°C

dependence $\sigma_t = f(\sigma_0)$ with $t \geq 5000$ h becomes rectilinear (see Fig. 36a), then for the nickel-chromium alloy, tested at 750°C, in spite of certain straightening of curves, the dependence indicated remains any curvilinear with relaxation time (to 20000 h) (Fig. 37a).

Dependence $\Delta\sigma = f(\sigma_0)$ in the common coordinate system is also expressed by broken line, but with sufficiently long relaxation time, it becomes rectilinear (Fig. 35f). Experimental data make it possible to note that the straightening of the lines of dependence $\Delta\sigma = f(\sigma_0)$ proceeds for steels of different mark/brands and temperatures in wide time interval - from 100-200 to 3000 h; however, even in this case for the dispersive hardening nickel-chromium alloy curves $\Delta\sigma - \sigma_0$ are not straightened/rectified completely even after 10000 h (see Fig. 37b). The curvilinear character of dependence $\sigma_t = f(\sigma_0)$ is observed for aluminum age-hardening alloys [174].

Thus, the ideal schematic (see Fig. 35b) it is valid (to the specific level σ_0) only for structurally stable alloys and for pure metals. In common/general/total form the dependence $\sigma_t = f(\sigma_0)$ is not rectilinear. More often it is possible to speak about the rectilinear character of the dependence between σ_t and the apparent stress σ'_0 , which corresponds to the beginning of II periods. But also here the straightness of lines $\sigma'_0 - \sigma_t$ is observed only in certain range of stresses (0.3-0.75) σ'_0 and of temperatures (0.25-0.5) T_{an} .

Did not obtain confirmation and expressed in his time Ya. S. Gintsburg [65] the position that the dependence $\sigma_t = f(\sigma_0)$ is subordinated to power law and can be described by equation $\sigma_t = a(\sigma_0)^p$.

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In actuality during graphing $\sigma_0 - \sigma_t$ in the dual logarithmic coordinate system in the majority of the cases is not observed the straightness of curves.

The given above experimental data and basic laws one should consider when selecting of initial stresses for the parts, intended for a work under conditions of stress relaxation. It is obvious that higher initial stresses, as a rule, provide the higher values of the remaining (final) stresses.

However, in this case, value of σ_0 must not exceed the value of elastic limit of material at this temperature [60, 65]. With the designation/purpose of the initial stresses in practice, usually they are oriented not to elastic limit, but to yield point $\sigma_{0.2}$. allow/assuming, as a rule, $\sigma_0 \leq 0.8 \sigma_{0.2}$ (with exception of the special cases, about which it will be said below).

Thus, the initial stress of relaxation depends on the level of the elastic properties of material. Based on this, some authors [47, 65, 95] express σ_0 in fractions of values σ_y or σ_t , considering that if necessary to compare the relaxation resistance of the number of materials is expedient to carry out comparative tests not at identical absolute values σ_0 , but with the identical value of ratio σ_0/σ_y (or σ_0/σ_t).

This approach undoubtedly is correct, since it makes it possible to more strictly compare the relaxation resistance of the series of the materials, which are strongly distinguished by their mechanical properties (σ_b , σ_t , σ_y) in the specific temperature range.

To L. P. Nikitinoy [95] is proposed the procedure of the selection of initial stresses, instituted on the principle presented and which gives the great possibilities of a comparative evaluation of diverse materials according to their resistivity of stress relaxation at different temperatures, besides with the expenditure of a minimum number of specimen/samples and, consequently, also the total time of tests.

In these cases fruitful/successful diagrams unlike those shown

on Fig. 35 construct in the relative coordinates:

$$\sigma_0/\sigma_r - \sigma_r; \sigma_0/\sigma_r - \sigma_r/\sigma_r; \sigma_0/\sigma_r - \Delta\sigma; \sigma_0/\sigma_r - \Delta\sigma/\sigma_r.$$

Examples of such graphs see Fig. 38, and also 83.

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L. P. Nikitin notes the rectilinear character of dependence it
notes the rectilinear character of dependence $\sigma_0/\sigma_{0,2} - \sigma_r/\sigma_{0,2}$ for
titanium alloy AT-3, structural 35KhV and austenitic steel Kh15N35VT.
However, in accordance with that presented above scarcely whether it
is possible to consider this straightness general law.

Until now, we examined the influence of initial stresses on
dependence $\sigma_r = f(\sigma_0)$ or $\Delta\tau = f(\sigma_0)$ with the initial stresses, not
exceeding $\sigma_y(\sigma_r)$, as this is observed in fasteners.

Under certain conditions frequently is noted the relaxation when
 $\sigma_0 > \sigma_r$, which can realize itself with the tensions [but not during
the tests of the annular specimen/samples (see Chapter III)]. Stress
relaxation when $\sigma_0 > \sigma_r$, for example, was observed in tests for
thermal fatigue with holding at the maximum temperature of cycle, and
also in special experiments [47].

Under these conditions the process of stress relaxation when $\sigma_0 > \sigma_r$ is characterized by the following special feature/peculiarities.

At high temperatures σ_0 , it is decreased to σ_r for the short time, calculated by minutes; at normal and moderately elevated temperatures the effective stress even during very long time can remain considerably more than σ_r .

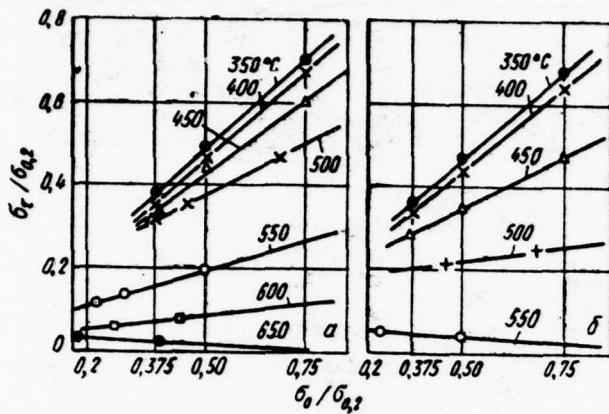


Fig. 38. Dependence $\sigma_t = f(\sigma_0)$ in relative coordinates [95]: a) relaxation time 1 h; b) 100 h.

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Furthermore, is observed the nonmonotonic character of dependence $\sigma_t = f(\sigma_0)$ with $\tau = \text{const}$. Real/actually, as it was shown above, relaxation curves for different σ_0 (large σ_0) can intersect. However, with an increase in the time, these curves at comparatively high temperatures usually are drawn off into one, which differs little from the curve, obtained when $\sigma_0 \approx \sigma_t$ (see Fig. 13).

It is necessary to keep in mind that at normal and moderately high temperatures, but with very high σ_0 , substantially exceeding σ_t , can be observed noticeable strengthening of metal and increase in

resistance of relaxation because of work hardening. When the nonriveted metal possesses smaller creep strength (relaxation), value $\Delta\sigma$ when $\sigma_0 \approx \sigma_r$ can prove to be more than when $\sigma_0 > \sigma_r$.

3. Time.

The effect of time on the course of the process of stress relaxation is closely related to other factors - initial stress and temperature, and also from the structural stability of the alloy being investigated. For example, with an increase in the temperature the effect of time factor is reinforced [60].

Relaxation curve in coordinates the stress, the time (see Fig. 3), distinctly is divided marked off into two sections, that correspond to two relaxation times. The first period, which is continued in the majority of the cases very short time, is characterized by a sharp voltage drop, what answers the descending section ab.

The second relaxation time whose duration considerably greater than the first, on the contrary, is characterized by the very moderate rate of voltage drop; relaxation it is curved on section bc for the high duration of testing it approaches an axle/axis of abscissas and in certain cases it generally attenuates, i.e., emerges

to horizontal section.

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It is known, numerous attempts at the mathematical generalization of the functional dependence of stress from the time (see Chapter I and II). For example, by I. A. Oding [96] were proposed the following equations of the first and second relaxation times:

$$\sigma_I = \sigma_0 e^{\frac{-kt}{1+pt}}, \quad (142)$$

$$\sigma_{II} = \sigma'_0 e^{\frac{t}{\tau_0}}, \quad (143)$$

where k and p - the constant coefficients, which depend on the properties of metal;

σ_0 and σ'_0 - initial stresses I and of II periods.

Analytical equations of this type have the overall deficiency: they do not reflect the possible effect of the structural transformations, which occur in age-hardening alloys at the specific temperatures. Meanwhile the developing in time structural transformations frequently significantly affect the character of the process of relaxation. Sc, if in strongly age-hardening alloys the

ccnstancy of the rate of relaxation is establish/installled comparatively rapidly, then in the weakly hardening alloys the stage cf fading the rate of relaxation sometimes lasts thousand of hours. Specific examples of such cases are given in g. VII, p. 4.

The structural instability of tested materials is developed during the study of the effect of time on dependence $\sigma_t=f(\sigma_0)$ and $\Delta\sigma=f(\sigma_0)$,
^ which was examined in detail above (see Fig. 35-37).

The duration of the unsteady relaxatior time is of essential interest, since with this is connected a practically important question concerning the minimum duration of experiment, sufficient for the subsequent extrapolation. The study of the numercus primary curves of relaxation shcws that for stable at operating temperature materials the duration of iritial period ussally varies from 200 to 1000 h. However, for the allcys, in which in the process of service structural transformations occur/flow/last slowly, the unsteady period can be continued ccnsiderably larger periods.

In connection with this the time of relaxation tests of the materials, intended for prclonged service, in our laboratories comprises 1000-3000 h.

Considerably less frequent than the relaxation test at elevated temperatures they lead to 10-20 thous h [93, 172] (i.e. to the actual service life of fasteners), and at normal temperature - to 50 thous h [70, 97]. The results of experiments in so high a duration (for example, see Fig. 84, 111) represent large value for testing of the correctness of extrapolation according to the results of less endurance tests.

4. Temperature.

Temperature effect on the process of stress relaxation in metals and alloys is completely great. As already mentioned in chapter I, analogous with creep distinguish stress relaxation with low (less than $0.25 T_{m\alpha}$), average ($0.25 T_{m\alpha} - 0.5 T_{m\alpha}$) and high (is more $0.5 T_{m\alpha}$) temperatures.

The mechanisms of relaxation of stresses (and of creep) in the temperature ranges indicated are different. Sc, the prevailing mechanism of low-temperature relaxation is slip and intersection of dislocations. Of stress relaxation in the mean temperature zone is determined by the intersection of dislocations, by overcoming by the dislocations of the barriers of Powers and, most importantly, by the

cross slip. The specific character of high-temperature relaxation are the diffusion mechanisms of the displacement of dislocations, the creeping of dislocations, the motion of screw dislocations, the viscous displacement of Cottrell's atmospheres (see Chapter I)¹.

FOOTNOTE¹. In more detail these questions are illuminated in G. Conrad's work [2, p. 57]. ENDFOOTNOTE.

It should be noted that the enumerated mechanisms differently are developed during short-term and prolonged relaxation, and also in metals with different lattice and in alloys with different degree of alloying. Specifically, in connection with this for some alloys, are characteristic nonmonotonic the curves of the dependences of resistance of relaxation from temperature (within limits to $0.25 T_{\text{m}}$). According to the curve 1 of Fig. 39, are observed the temperature ranges, in which the processes of relaxation and creep are inhibited as a result of strain aging, formation of preseparations (Guignet-Preston's zone), etc.

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An illustration can serve the real temperature curve of relaxation 4 for austenitic steel of the type Kh18N10T with $\sigma_0=350 \text{ MN/m}^2$ (35 kg/mm^2) and $\tau=24 \text{ h}$ (on L. B. Getsova's data).

In other cases temperature dependence of resistance of relaxation (creep) is expressed monotonic curved 2 and 3, Fig. 39.

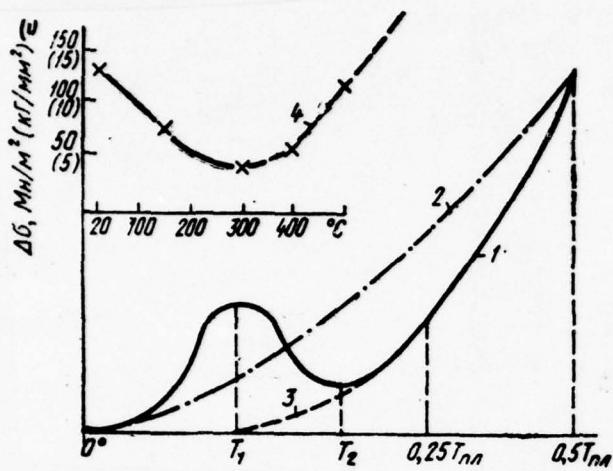
Fig. 39. Dependence $\Delta\sigma=f(T)$.Key: (1). $\text{MN/m}^2 (\text{kg/mm}^2)$.

Table 10. Temperature of minimum (T_1) and maximum (T_2) resistance of the relaxation of some alloys in the zone of temperatures (0–0.25) T_{nn}

Материал (N)	T_1		T_2	
	°C	°K	°C	°K
Железо Армко (1)	-70	203	+20	293
Сплав Al-Si (силимин) (2)	-70	203	+20	293
Титановые α -сплавы (4)	+20	293	300–350	573–623
Высокопрочные конструкционные стали (5)	+20	293	150–250	423–523
Аустенитная сталь (6)	220	293	300	573
Х18Н10Т	400	673	500–550	773–823
Сплавы на никелевой основе . . . (7) . . .				

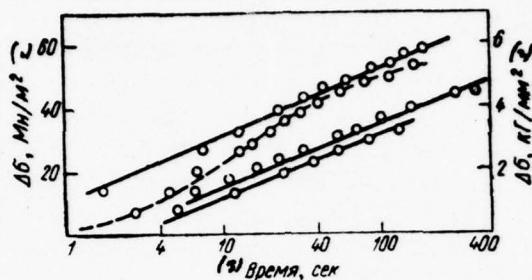
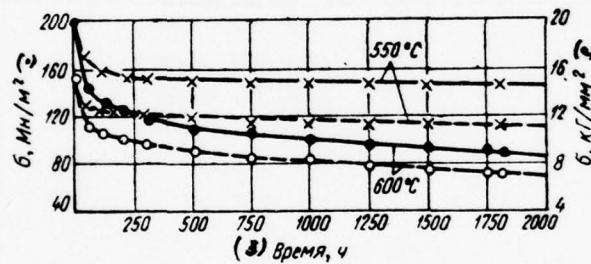
Key: (1). Material. (2). Iron of Armcos. (3). Alloy Al-Si (siluminum). (4). Titanium α -alloys. (5). High-strength structural steels. (6). Austenitic steel Kh18N10T. (7). Nickel base alloys.

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A similar form of curves is characteristic for alloys whose processes of strain aging either not at all are observed (curve 2), or they occur/flow/last so intensely that the low-temperature relaxation (creep) is virtually absent (curve 3).

Table 10 gives the reduced temperatures, which correspond to the basic zones of a curve of type 1 (Fig. 39).

The insignificant intensity of stress relaxation in metals at temperatures lower than 0°C long time served as occasion for doubts of its existence. However, the processes of stress relaxation real/actually occur at the temperatures lower than 0°C. So, Feltam [98] studied relaxation in iron of Armko (Bis. 40), cobalt, copper, α-brass and magnesium alloy with the temperatures up to - 196°, S. V. Ya. Zubov and S. V. Grachev [97] in high-strength steel of brands 70KhS and 70S3KhMVA at temperature of -96°C, B. A. Potekhin and I. I. Bogachev [99] in austenitic steel of the type 3Kh10GYu also at -96°C.

Fig. 40. Short-term stress relaxation in ABMCO iron with $-73^\circ C$ [98].Key: (1). MN/m^2 . (2). kg/mm^2 . (3). Time, s.Fig. 41. Primary curves of stress relaxation in austenitic steel Kh18N25S2 with σ_0 , MN/m^2 (kg/mm^2): solid lines - 200 (20); dash - 150 (15).Key: (1). MN/m^2 . (2). kg/mm^2 . (3). Time, h.

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Speaking about mean temperature region ($0.25-0.5 T_{in}$, it should

be noted that an increase in testing temperature affects the primary curves of relaxation as follows: it is elongated I relaxation time it increases the angle of slope II (rectilinear) sections. This is evident based on the example of heat-resistant austenitic steel of brand Kh18N25S2, tested at 550 and 600°C (Fig. 41). With further increase in the temperature (higher than 0.5 $T_{m\alpha}$) the process of relaxation generally can be restricted to I period, which indicates the full/total/complete relaxation softening of metal. The temperature, calling this phase of relaxation, is of known interest. But from an engineering point of view larger value has the temperature, which corresponds to the initial stage of softening - when begins essential drop σ_t , but still is observed completely stable II relaxation time.

The available experimental data show that the softening of pure metals, steels and alloys under the effect of the temperature under conditions of stress relaxation occur/flow/lasts considerably more intense than under conditions of creep. Are given below the temperature intervals of relaxation softening for typical austenitic steels and nickel base alloys:

Аустенитные стали с карбидным упрочнением	(у)	650—700	°C
То же, с интерметаллидным	(ч)	700—750	
Никельхромовые сплавы:			
слабо упрочненные	(у)	750—800	
средне >	(ж)	800—850	
сильно >	(б)	> 850	

Key: (1). Austenitic steels with carbide strengthening. (2). The same, with intermetallic. (3). Nickel-chromium alloys. (4). weakly reinforced. (5). average. (6). Strong.

Although the temperature of the beginning of relaxation softening for steels with intermetallic phase approximately the same as during creep ($\sim 700^{\circ}\text{C}$), the intensity of the course of the process of stress relaxation with further increase in the temperature is considerably higher. In connection with this the possibility of using such steels with 750°C as relaxation-resistant material with prolonged service life virtually drops off. This is evident based on the example of steel Kh15N25V4T (Fig. 42), which at the temperature indicated only 1000 h after retains only 30-35% from initial stress¹.

FOOTNOTE 1. More detailed data on temperature effect on the relaxation resistance of heat-resistant steels and nickel-chromium alloys are given in chapter VI, p. 4. ENDFOOTNOTE.

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If we consider that creep exists an alternation of two opposite processes - softening under the effect of temperature and strengthening from plastic deformation (work hardening), then the

noted above fact completely explicable. Under conditions of relaxation of stresses (with the invariability of initial total deformation) the weakening action of temperature barely resists the strengthened/hardened effect of the plastic deformation (see Chapter I).

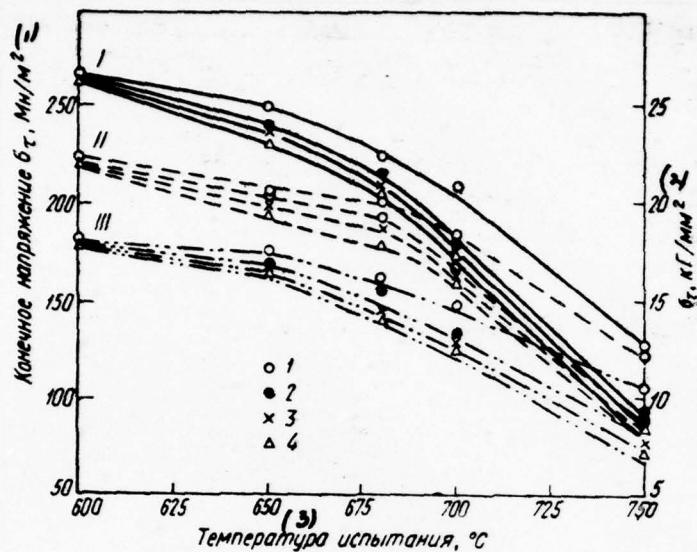


Fig. 42. The diagram of the dependence of value σ_t from the basic parameters of testing (t , σ_0 , T) for austenitic steel Kh15N25V4T: I - $\sigma_0 = 300 \text{ MN/m}^2$ (30 kg/mm²); II - 250 (25); III - 200 (20); 1 - 500 h; 2 - 1000 h; 3 - 1500 h; 4 - 2000 h.

Key: (1). Final stress σ_t , MN/m². (2). kg/mm². (3). Testing temperature, by °C.

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Ya. S. Gintsburg [65] introduces the concept of the critical temperature of relaxation of stresses T_R . Regarding the author, this is the temperature of which the value of coefficient S_0 , which

characterizes the resistivity of relaxation in I period, remains constant with any value of σ_0 . This formulation is sufficiently not defined, especially as at moderately high temperatures, as is known, initial stress of σ_0 not at all affects value S_0 .

The temperature dependence of different characteristics of relaxation was studied by many researchers. Sc. F. I. Aleshkin [100] gives the temperature dependence of the relative stress of relaxation $R_t = (\sigma_t/\sigma_0) 100$ (the "resource, lifetime of stresses") in the form

$$R_t = 100 \left[1 - \frac{d}{T} \times \exp\left(1 - \frac{c}{T}\right) \right], \quad (144)$$

where c and d - coefficients.

L. P. Nikitin [95] it investigated the temperature dependence of the relaxation time τ_σ , cf necessary for achievement specific level of relative stress σ_t/σ_0 . Processing the results of the tests of titanium alloy (Fig. 43), of pearlitic and austenitic steels showed that between time τ_σ and t there is an exponential dependence.

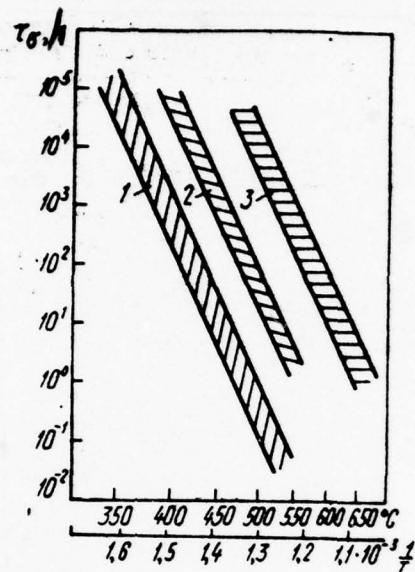


Fig. 43. The temperature dependence of the relaxation time, necessary for decreasing the stress σ_0 : 1 - to 0.8 σ_0 ; 2 - to 0.5 σ_0 ; 3 - to zero.

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Presented in p. 2-4 data sufficiently convincingly attest about the fact that the effect on the process of the relaxation of three main parameters; stress, temperature and time is closely interconnected.

Therefore logically researchers' tendency to present the dependence of experimental data simultaneously on all enumerated parameters, for example $\sigma_t = f(t, \sigma_0, \tau)$.

By most convenient is a diagram of the type given to Fig. 42, where is represented a change of value σ_r as function of the temperature, at different initial stresses. Curves for different duration of tests (in this case from 500 to 2000 h), obtained at each value of σ_0 , form the beam, which diverges in the direction of high temperatures. The latter fact confirms that with an increase in the temperature the effect of time on relaxation resistance is reinforced. The beams of curves for different σ_0 in high-temperature range, on the contrary, converge, which indicates the decrease of effect of σ_0 on temperature.

Earlier by us she was indicated [60] that must exist the definite dependence between the basic parameters, defining the process of relaxation - by stress, by temperature and time, similarly, as it takes place under conditions of creep. Was proposed the diagram, connecting simultaneously these three parameters in convenient for a designer form (Fig. 44a).

According to this diagram it is not difficult to determine the time, necessary for achievement of the assigned magnitude of the final stress of σ_r at different temperatures t , or to determine (with the given σ_0) value σ_r on the assigned/prescribed service life.

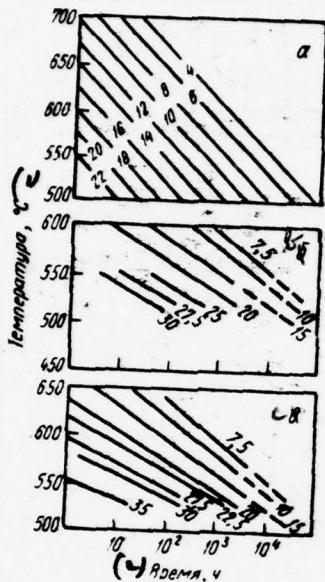


Fig. 44. Diagram of dependence $\sigma-\tau-t$: a) schematic diagram; b) chrome-vanadium steel; c) chrome-molybdenum-vanadium steel (numbers by the curves - σ_0 , $MN/m^2 \cdot 10^{-1}$).

Key: (1). Temperature, °C. (2). Time, h.

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Taking into account straightness and parallelism of the lines of equal stresses, which encompass wide range of stress [from 220 to 40 MN/m^2 (22-4 kg/mm²)], the sections of straight lines in the right side of the diagram (corresponding to the greatest durations) during

its construction can be extrapolated.

Last/latter literature data [101] confirm the presence of parametric dependence $\sigma-t-\tau$, which begins to be applied during processing of the results of relaxation tests. Figures 44 shows such curve/graphs for low-alloy steel. If the first of these graphs (Fig. 44b) completely confirms fundamental diagram in Fig. 44a, then Fig. 44c differs from it in that the lines of equal stresses here are not strictly parallel, but somewhat they diverge in the region of highest temperatures and short relaxation time. However, this fact must not prevent the practical use of the described method.

5. Scale factor.

The study of the effect of the size/dimensions of specimen/sample (part) on the intensity of the processes of stress relaxation is reflected in the very limited number of works [96, 41, s. 332]. Experiments of Oding and Furdukskiy [96] were given at 600°C under conditions of the elongation of the specimen/samples of different length (50 and 100 mm) and of diameter (5 and 10 mm), manufactured from steels Kh18N12M3T, Kh18N1CT and 4Kh15N7G7PM (EI388).

Test results averaged by the method of least squares. In this

case, was reveal/detected certain reduction in the relaxation resistance of the specimen/samples of smaller size/dimensions. Was made the assumption that different relaxation life of the specimen/samples of different size/dimensions was connected with the local character of the course of small plastic deformations at high temperatures.

For confirmation this, were carried out special experiments with the specimen/samples, or the surface of working part of which through every 10 mm were applied the impressions by Vickers's tool. The distance between impressions measured with high accuracy/precision before and after relaxation test.

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Figures 45 gives the graph of the distribution of plastic deformation along the length of the specimen/sample made of steel Kh18N12M3T, which was testing at 600°C for 500 h. From Fig. 45 it follows that under conditions of relaxation is observed the considerable scatter of weak and strong volumes along the length and, apparently, over the section/cut of specimen/sample. Hence it follows that in the specimen/samples of a comparatively large diameter (length) the resistivity of relaxation must be averaged by various volumes. At the same time in fine/thin and especially in short

specimen/samples the averaging of the distribution of weak and strong volumes is hindered/hindered. Therefore in the first case relaxation curves are stable, secondly is observed their significant scatter. Furthermore, the locality of plastic deformation can bring in a series of cases to certain reduction in the relaxation resistance of the specimen/samples of small size/dimensions, since the probability of the accumulation of weak volumes over the section/cut of specimen/sample in the quantity, sufficient for its softening, in fine/thin specimen/samples the value is more than in the specimen/samples of large diameter. At the same time the specimen/samples of a small diameter have this probability is greater, the greater the length of specimen/sample.

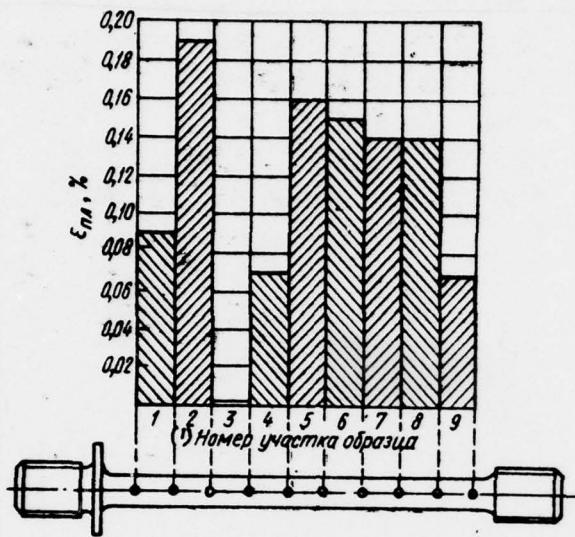


Fig. 45. Graph of the distribution of plastic deformation during relaxation of stresses [96].

Key: (1). Number of the section of specimen/sample.

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It was establish/install also, that the form of cross section, including the presence of thread on surface, do not have noticeable effect on relaxation resistance.

I. P. Baushis [41, p. 332] investigated resistance of relaxation at different temperatures under conditions of compressing the specimen/samples of different length and diameter made of carbon steel 20, 45, 48, 60S2 and coppers of brand M4 at 300 and 400°C. The diameter of specimen/samples was varied within the limits of 5-10 mm, length - from 10 to 160 mm.

It is establish/install, that with an increase in the diameter the intensity of the process of relaxation increases, especially on the second section of curves (Fig. 46). An increase in the length of specimen/sample also leads to the acceleration of the processes of relaxation; however, this acceleration is observed only on the second section (Fig. 46).

Howled proposed the following approximation of the obtained

experimental data:

$$\sigma = \sigma_0 - \phi_1(l) \phi_2(F) f(\sigma_0, \tau, t), \quad (145)$$

where $\phi_1(l)$ and $\phi_2(F)$ - functions of length and cross-sectional area of specimen/sample.

$f(\sigma_0, \tau, t)$ - the function of the parameters of the testing: initial stress σ_0 , time τ and temperature t .

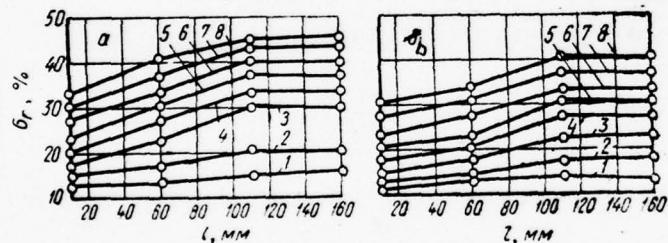


Fig. 46. Effect of the length of specimen/sample ($d=10$ mm), on relative value of an incidence/drop in stress in steels 20 (a) and 45 (b) with $t=400^\circ\text{C}$; $\sigma_0=150 \text{ MN/m}^2$ (15 kg/mm^2). The time of relaxation, h : 1 - 1; 2 - 5; 3 - 10; 4 - 24; 5 - 48; 6 - 72; 7 - 96; 8 - 120 [41].

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The form of the function ϕ_1 and ϕ_2 was selected on the basis result in tests

$$\varphi_1(l) = -\frac{A_1}{B_1 + \frac{C_1}{l}}, \quad (146)$$

$$\varphi_2(F) = -\frac{A_2}{B_2 + \frac{C_2}{F}}, \quad (147)$$

where $A_1, B_1, A_2, B_2, C_2, C_1$ - the coefficients, depending on the physical and mechanical properties of material.

The values of these coefficients for investigated carbon steel and copper at 300 and 400°C comprised

$$A_1 = B_1 = 4,0; C_1 = 1 \text{ cm}^{-1}; A_2 = B_2 = 2,0; C_2 = 0,1 \text{ cm}^{-2}.$$

Thus, the conducted investigations do not make it possible to make single-valued conclusions about the effect of scale factor on the relaxation life of different materials. Apparently, it is analogous with creep, scale factor can be revealed as a result: a) a nonuniform distribution of the creep strength in different microvolumes, which is differently developed in the specimen/samples of different dimensions; b) different the effect of surface condition of the specimen/samples of different dimensions (effect of work hardening, oxidation); c) the facilitation of the output/yield of dislocations on surface during an increase in the surface to volume ratio.

Different conclusions of the researchers [96; 41 s. 332] are explained not only manifestation of scale factor with relaxation under conditions of compression and elongation, but also by special feature/peculiarities of behavior under these conditions of the tested materials (copper, pearlitic and austenitic steels).

6. Basic criteria of stress relaxation.

For the evaluation of the relaxation resistance of materials, serve the following criteria: the remaining stress; the voltage drop; the resource/lifetime of stresses; the rate of relaxation; the limit of relaxation; the conditional coefficients of relaxation.

Remaining stress. Stress σ_t , "remaining" in part or test specimen during a certain time interval from the torque/moment of the loading of part (specimen/sample) by initial stress σ_0 , is most frequently utilized as the numerical characteristic of the relaxation resistance of metals and alloys.

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In spite of this, until now, there is no single term for a

designation σ_r . Besides the remaining stress, value σ_r is called the residual, current and final stresses or simply by the stress of relaxation.

Term residual stress unavoidably will lead to confusion with the taking root concepts of the residual stresses of the 1st and 2nd kind. Term the current stress is unsuccessful in semantic sense and, furthermore, are caused associations with yield point. Finally, stress σ_r it is final not always, but only when it coincides with the termination of testing or period of operation. For these reasons, we adhere to the term the remaining stress, which is successful.

Value σ_r during this period of time τ depends on the initial stress: $\sigma_r = f(\sigma_0)$. This dependence is analyzed in detail in p. 2 of Chapter IV. Therefore, giving numerical values σ_r , it is necessary to indicate, with what precisely σ_0 they were obtained, which, unfortunately not always is fulfilled.

Basic advantage of the remaining stress as the criterion of relaxation consists in the fact that value σ_r is obtained directly from experiment and does not require additional mathematical treatment.

The voltage drop for the caused time interval τ ($\Delta\sigma = \sigma_0 - \sigma_r$)

together with that remaining stress σ_t can be considered the basic criterion of relaxation resistance, which were being applied even in the early period of the study of the process of relaxation [3, 102]. Just as σ_t , value of $\Delta\sigma$ is the function of the initial stress: $\Delta\sigma=f(\sigma_0)$.

By indirect characteristic of relaxation, in the principle of analogous ~~helical spring~~ ^{$\Delta\sigma$} under the effect of compressive force. As is known, this test procedure widely is applied for the evaluation of the relaxation resistance of snap-springs steel and alloys.

At the same time the value of $\Delta\sigma$ and σ_t for this time τ they insufficiently fully characterize a comparative resistivity of the relaxation of the materials being investigated, since they reflect either preceding/previous or further course of the process of relaxation.

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For judgment about kinetics of the drop of stresses, it is necessary to know $\Delta\sigma$ or σ_t for different time intervals, that constitute 0.05; 0.1; 0.2; 0.5 from full/total/complete time testing or assigned/prescribed service life.

Resource/lifetime of stresses. In a series of cases, a reduction in the stress in the process of relaxation is convenient to represent in relative values from initial stress. Relative value of the remaining stresses, expressed in percentages, is was been called the "resource/lifetime of stresses":

$$R_t = \frac{\sigma_t}{\sigma_0} \cdot 100\%.$$

By I. A. Oding and F. I. Aleshkin [10, 100] is proposed the generalized diagram of the resource/lifetime of the stresses of relaxation in coordinates $R_t - t$ (Fig. 47) who makes it possible to determine the relative remaining stress at the any moment of time t . Diagram is valid under the assumption that dependence $\sigma_t = f(\sigma_0)$ is rectilinear. In this case absolute value σ_t can be calculated on curve $\sigma_t / \sigma_0 - t$ at any value of σ_0 . However, in the general case dependence $\sigma_t = f(\sigma_0)$, as were shown on p. 2 of Chapter IV, is not rectilinear. Since the degree of change σ_t depending on level σ_0 can be in actuality different, a change of value σ_0 even not between very wide limits can significantly influence the character by curve $\sigma_t / \sigma_0 - t$.

In communication/ccnnection by F. I. Aleshkin [103] presented was subsequently developed the procedure of calculation of the stresses in deviation domains from straightness and was given nomogram for determining the correction factor for additional stress which substantially complicates entire method.

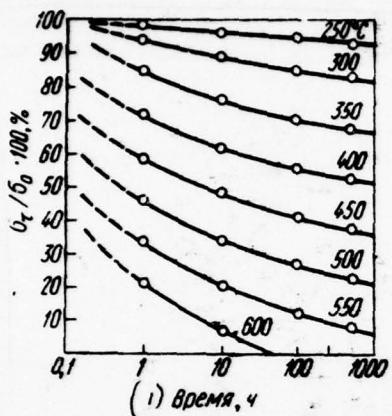


Fig. 47. Diagram of the "resource/lifetime cf stresses" (relative stress $\sigma_t/\sigma_0 \cdot 100\%$) for AFMCO iron [100] at different temperatures.

Key: (1). Time, h.

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A. M. Borzdyka and V. A. Uzhik proposed [60] on the diagram of the reserve of stresses instead of averaged curves $\sigma_t/\sigma_0 - \tau$ (see Fig. 47) to apply the band of scatter for different values σ_0 . This diagram for the nickel-chromium alloy Kan77Yu, tested with the initial stresses, which comprise (0.3-0.65) σ_0 at temperatures of 600-650°C and (0.2-0.5) σ_0 at 700°C, is given to Fig. 48. The scatter of the experimental points, which correspond to the values σ_0 indicated, is sufficiently great, in particular at higher temperature

(700°C). Consequently, the second version of the diagram of the resource/lifetime of stresses is more advisable.

Rate of relaxation. Distinguish "true", the "average" and "logarithmic" rates of relaxation [60, 104].

True (or "instantaneous") airspeed of relaxation in any point curve stress - the time

$$\sigma_t = - \frac{1}{\tau_0} \sigma'_0 e^{-\frac{\tau}{\tau_0}} \quad (148)$$

do not virtually determine.

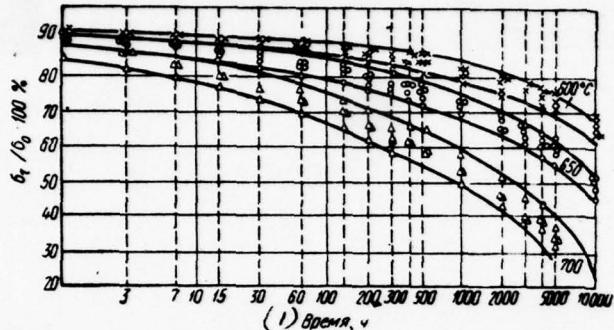


Fig. 48. The diagram of a change in relative stress ($\sigma_t/\sigma_0 \cdot 100$) in time for the nickel-chromium alloy KhN77TYu (by curves is limited the band of the scatter of the experimental points for different values σ_0).

Key: (1). Time, h.

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They usually calculate the average speed of relaxation (v_r) for certain time interval, limited by two points (τ_2 and τ_1) in primary relaxation curve:

$$v_r = \frac{\sigma_1 - \sigma_2}{\tau_2 - \tau_1}. \quad (149)$$

Value v_r measures in unity of the stress, in reference to time

unit, or in percentages in hour.

The logarithmic rate of relaxation [3] is determined by the equation

$$k = \frac{\ln \sigma_1 - \ln \sigma_2}{\tau_2 - \tau_1} \quad (150)$$

and it is expressed in values h^{-1} or min^{-1} .

Value, inverse to k :

$$\tau_0 = \frac{\tau_2 - \tau_1}{\ln \sigma_1 - \ln \sigma_2} \quad (151)$$

by the name "time of relaxation" [3] earlier also was applied as the characteristic of relaxation.

I. A. Odintsov and F. I. Aleshkin establish/install on the iron of Armos linear (in the logarithmic coordinate system) dependence of the rate of relaxation v_r on the time of testing. Temperature dependence v_r is expressed on the logarithmic graph by broken line [100].

On data of Ya. S. Gintsburg [65], dependence $\sigma_0 - v_r$ in dual logarithmic coordinates is described by straight lines (Fig. 49a),

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whence by it was made assumption about the presence between σ_0 and v_r of exponential commutation/connection, similar available between σ and v_n under conditions of creep ($v_n = A\sigma_0^n$).

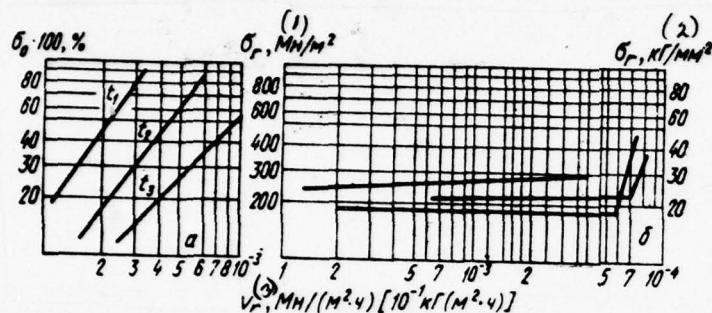


Fig. 49. Graph/diagrams of dependence $\sigma_0 - \sigma_r$: a) on data of Ya. S. Gintsburg [65]; b) on data [60].

Key: (1). MN/m^2 . (2). kg/mm^2 . (3). $MN/(m^2 \cdot h) [10^{-1} kgf(m^2 \cdot h)]$.

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If this dependence for the process of relaxation actually existed, then of curve/graphs $\ln\sigma_0 - \ln\sigma_r$ under the condition of replacing the relative values of σ_0 along the axis of ordinates by absolute values.

However, dependence $v_r = A\sigma_0^n$, did not obtain confirmation in other researchers' works. Attempts at the construction of logarithmic graphs $\sigma_0 - \sigma_r$ on numerous experimental data did not give the satisfactory results: either obtained straight lines lay down almost

in parallel to the axle, axis of abscissas or lines were broken lines in region are most high stresses and rates of relaxation (Fig. 49b).

It should be pointed out that the existence of dependence $v_r = A\sigma_0^n$ would contradict established facts about the insignificance of effect of σ_0 on v_r in II relaxation time and practical parallelism of the primary curves (within the limits, corresponding to II nature), obtained at different values σ_0 (see Chapter IV, p. 2).

Limit of relaxation. This term apply, at least, in three versions: the true (physical) limit of stress relaxation; apparent stress for given speed relaxation; the conditional (technical) limit of relaxation (on stress).

Under the true (physical, theoretical) limit of stress relaxation by analogy with physical creep limit, is understood the maximum initial stress, yet not calling of relaxation [96]. This characteristic is not virtually applied, and the existence of the physical limit of relaxation thus far does not have sufficient experimental confirmation.

Also did not win acceptance the conditional limit of relaxation according to Ya. S. Gintzburg [65], representing the initial stress, leading to the assigned/prescribed average speed of relaxation on the

straight portion of primary curve $\sigma-r$ and determined on logarithmic graph σ_0-v_r (see Fig. 49). As it was noted earlier, the existence of the power dependency between the rate of relaxation v_r and initial stress σ_0 is taken in doubt.

The representation of the technical limit of relaxation σ_r gives the schematic diagram Fig. 35, from which it is evident that the lines, which reflect dependences $\sigma_r=f(\sigma_0)$ or $\Delta\sigma=f(\sigma_0)$ for different time intervals r_1-r_4 , are converged fan-shaped at certain point, which lies on the axle/axis of the initial stresses.

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Cut from point of intersection to the origin of coordinates characterizes the value of the technical limit of relaxation which is also called the conditional limit of relaxation on stress [92, p. 5]¹.

FOOTNOTE 1. The technical limit of relaxation can be also determined according to dependence $\Delta\sigma=f(\sigma_0)$, where σ'_0 - conditional initial stress of II relaxation times. ENDFOOTNOTE.

One should specify that for real alloys the intersection of pencil of straight lines $\sigma_0-\sigma_r$ or $\sigma_0-\Delta\sigma$ with the axle/axis of

ordinates (Fig. 50) in the majority of the cases occurs not at point, but in the very narrow region of the initial stresses - within the limits of 5-20 MN/m² (0.5-2 kg/mm²).

The basic reason for this scatter, if we do not consider unavoidable experimental errors, apparently, it consists of the noticed by I. A. Odinc and T. M. Vclkova [92, s. 5] shift of point of intersection with the axis/axis of the ordinates of straight lines $\epsilon_0-\Delta\sigma$, that correspond to the greatest durations of testing. The phenomenon indicated the authors relate because of the insufficient structural stability of tested materials.

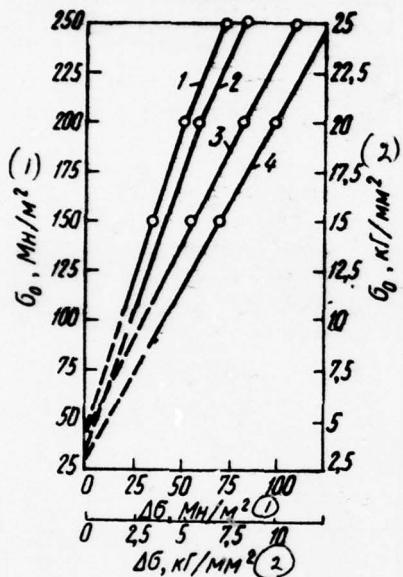


Fig. 50. Graphic determination of the conditional limit of relaxation σ_r from curves $\sigma_0-\Delta\sigma$ for steel Kh15N35VMT, $t=650^\circ\text{C}$. The relaxation time, h: 1 - 500; 2 - 1000; 3 - 5000; 4 - 1000.

Key: (1). MN/m². (2). kg/mm².

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This point is confirmed by experimental data for a series of commercially pure metals (iron of Armcos, copper, nickel, titanium), for which the straight lines $\sigma_0-\Delta\sigma$ on graphs (cm Fig. 50) intersect sufficiently accurately with the axle/axis of the initial stresses at

one point.

It should be noted that the absolute value of the technical limit of relaxation, as a rule, it is very small. So, for austenitic steel Kh15N35VMT at 650°C $\sigma_r = 30 \div 40 \text{ MN/m}^2$ (3-4 kg/mm²) (Fig. 50); for the heat-resistant nickel-chromium alloy KhN65VMTYu when 750° $\sigma_r = 25 \text{ MN/m}^2$ (2.5 kg/mm²); for titanium alloy ATZ [42] at 450°C 80, at 550°C 20 MN/m² (8 and 2 kg/mm²). It is such low values σ_r they represent known inconveniences during its practical use for design calculations.

Coefficients of relaxation. By some researchers for the more detailed evaluation of relaxation properties are proposed conditional coefficients. So, B. M. Rcvinskiy in his theoretical works as the criterion of relaxation utilizes value $R = (1/p) - 1$, where p - the parameter, which characterizes the intensity of relaxation process and depending on material and his structural state (see page 21).

The coefficient of relaxation life θ_r is the time, which requires for a reduction in the stress σ_0 to 10 MN/m² (1 kg/mm²) ($\ln\sigma_r=0$) [92, s. 87]. It are determined graphically - by the prolongation of the primary curve $\ln\sigma - t$ before intersection with time axis. Coefficient θ_r is connected with the conditional initial stress of II periods of σ'_0 by the equation

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$$\theta_r = \tau_0 \ln \sigma'_0. \quad (152)$$

Stress σ'_0 with sufficient accuracy/precision is also determined graphically - by the prolongation of the straight portion of primary curve to the left before intersection with the axle/axis of the coordinates (see Fig. 3). The cut, intercept, detached on this axle/axis, corresponds to value of σ'_0 .

The ratio of the initial stress of II periods σ'_0 to initial stress (I periods) σ_0 was named I. A. Oding the "coefficient of intergranular relaxation": $s_0 = \sigma'_0 / \sigma_0$. This sense characterizes the resistivity of metal in the first relaxation time.

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Another criterion of relaxation, proposed I. A. Oding, "coefficient of intragranular stability" $\tau_0 = 1 / \tan \alpha$, where α - angle of the slope of straight portion curved linear to the axle/axis of the abscissas (see Fig. 67). This coefficient characterizes the resistivity of metal in the second relaxation time. Actually τ_0 - time during which the stress level σ_0 is decreased in e times.

Names both of coefficients are connected with those developed in their time by I. A. Oding and his school by the representations about the fact that I relaxation time is connected with diffusion processes and plastic deformation passes in essence at grain boundaries, and relaxation in II period is caused by the shift processes, which occur inside the grains.

However, in works of Mak Lin [17], of Cottrell [7] and V. M. Rosenberg [20] it is shown, that the mutual displacement of grains during creep is caused by the processes of slip and creeping of dislocations within grains and connected with any new mechanism of deformation. The investigations of other authors also show that in the region of "average" temperatures ($0.25\text{--}0.5 \cdot T_{\text{m}}$) the intragranular dislocation-shift processes in metal occur both in the first and second relaxation times. Consequently, the coefficients of intergranular relaxation life (S_0) and of intragranular stability (τ_0), obviously, do not have that physical value, which by them was assigned in previous works.

Both coefficients, real/actually they at the same time characterize the intensity of relaxation process in its different stages.

Therefore we consider possible in the necessary cases to use

coefficients S_0 and τ_0 for the additional characteristic of the relaxation resistance of the materials being investigated, without giving to them, however, initial physical sense.

As far as coefficient is concerned θ_r , it seemingly expresses entire resource/lifetime of the relaxation resistance of metal, its relaxation life. Thus, appropriated to coefficient θ_r name can be considered successful.

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On this stage of the study of the process of stress relaxation, one should recognize by its basic criteria drop in the voltage $\Delta\epsilon$ and remaining stress σ_r . In this case, for practical target/purposes, are more preferable the absolute values of these characteristics, for theoretical ones - relative.

The conditional (technical) limit of relaxation σ_r is in principle important and necessary characteristic. However, on reasons presented above it thus far cannot serve as the criterion of relaxation resistance and all the more initial value for design calculations. Is necessary further accumulation of experimental data, and also perfection/improvement of the procedure of determination σ_r .

Kinetics of the process of stress relaxation on its different stages anything better characterizes the average rate of relaxation v_r . So that the application/use of this criterion would become more effective, it is necessary to regulate the allowable speeds of relaxation for specific operating conditions.

As concerns the conditional coefficients of relaxation, then some of them, apparently, can be highly useful during the study of the other one or parts of the process of relaxation. At the same time these coefficients by themselves cannot serve as the independent criterion of the relaxation resistance of metals and alloys.

One should specify that under conditions of cyclic stress relaxation appears the need for the additional criteria which are examined below.

Chapter V.

CYCLIC STRESS RELAXATION.

1. Relaxation with repeated loadings.

During the operation of power machinery equipment, sufficiently frequently are created the conditions of stress relaxation with repeated loadings. Such conditions are observed, for example, during each starting/launching of unit in the unevenly warmed thoroughly parts: the thermal stresses in these parts cyclically relax.

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Furthermore, in connection with the inadmissibility of the weakening of fastening during operation periodically it is necessary to stretch. These operations must be fulfilled, also, at high temperatures.

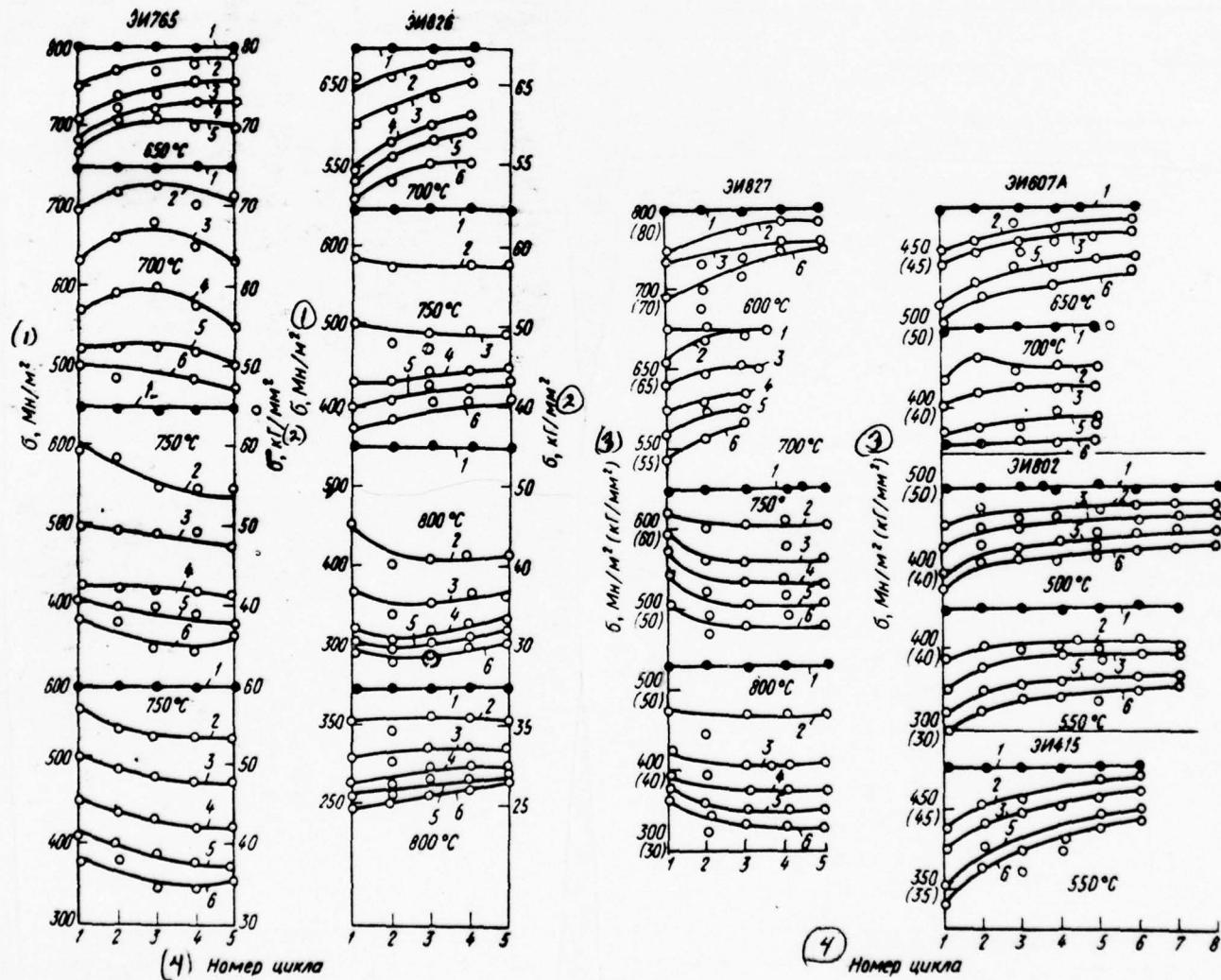


Fig. 51.

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Fig. 51. The dependence of the remaining stress σ_t from the number of the cycle of loading and relaxation time of heat-resistant alloys,
min: 1 - 0; 2 - 1; 3 - 5; 4 - 15; 5 - 30; 6 - 60.

Key: (1). MN/m². (2). k \cdot s/m². (3). MN/m² (kg/mm²). (4). Number of cycle.

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The repeated pull of the attachment parts of power machinery equipment are manufactured also after preventive and major overhauls, not less frequent than one time per annum. In the majority of the cases, repeated loading is manufactured to initial stress level.

Experimental works on the study of relaxation with repeated loadings are conducted in recent years very intensely [30, 105-107]. As a result of these investigations, it is established, that resistance of this material of relaxation with repeated loadings is changed in dependence on testing temperature, initial stress, number of loadings and interval between them.

The complex dependence of resistance of repeated relaxation on test conditions and material is connected with the specific character of the cyclic instability of materials, in turn, which depends on the temperature, and by the laws governing creep at alternating loading. Aforesaid is illustrated by data on short-term relaxation with the repeated loadings of different materials over a wide range of temperatures [108]. Tests carried out under conditions of elongation at the constant values of the initial stress $\sigma_{0(n)}=\text{const}$, moreover σ_0 was varied ($\sigma_0 > \sigma_{0,2}$ and $\sigma_0 < \sigma_{0,2}$). Time between the stress applications was 1 h. The results of individual tests are given in

Fig. 51.

The analysis of the obtained dependences of the remaining stress from a number of loadings shows that depending on testing temperature the intensity of stress relaxation either is decreased or it increases, or it remains constant/invariable. This behavior of materials can be named "cyclic instability under conditions of repeated relaxation". The character of cyclic instability can be changed with an increase in the number of cycles. Thus, for instance, at 700°C alloy KhN70VMYUT during the first two cycles cyclically is strengthened, then cyclically is softened¹.

FOOTNOTE 1. Similar behavior of alloy was observed also with repeated loadings for 1500 h [105]; however, the stages of softening were not revealed/detected. ENDFOOTNOTE.

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The character of cyclic instability, as can be seen from Table 11, is changed during an increase in the temperature of the testing: the investigated materials at comparatively low temperatures (corresponding to the temperatures, at which usually they work fasteners) they are cyclically hardened. At the temperatures, close to tempering temperature, is observed the cyclic softening of materials under conditions of repeated relaxation.

Table 11. Test results for cyclic short-term relaxation.

(1) Материал	(2) Темпера- тура, °C	(3) Характер изменения $\Delta\sigma$ с увеличением числа циклов
20ХНМВФ (ЭИ415)	550 650	(4) Циклическое упрочнение (5) Циклическое разупрочнение
Х12ВНМФ (ЭИ802)	500 550	(4) Циклическое упрочнение * * *
ХН80ТБЮ (ЭИ607А)	650 700	(6) > > Незначительное циклическое упрочне- ние
ХН70ВМЮТ (ЭИ765)	650 700 750	(4) Циклическое упрочнение (7) Вначале циклическое упрочнение, за- тем циклическое разупрочнение (8) Циклическое разупрочнение
ХН70ВМФЮ (ЭИ826)	700 750 800	(4) Циклическое упрочнение (5) Незначительное циклическое упрочне- ние (8) Циклическая стабильность
ХН75ВМФЮ (ЭИ827)	600 700 750 800 900	(4) Циклическое упрочнение (6) > > Незначительное циклическое упрочне- ние (7) Циклическое разупрочнение (8) Циклическая стабильность

Key: (1). Material. (2). Temperature, °C. (3). Character of change in $\Delta\sigma$ with increase in number of cycles. (4). Cyclic strengthening. (5). Cyclic softening. (6). Insignificant cyclic strengthening. (7). At first cyclic strengthening, then cyclic softening. (8). Cyclic stability.

At the very high temperatures, close to the temperatures of recrystallizations, at which the processes of creep are developed without strengthening (rate of rapid creep does not depend on time), materials behave as cyclically stable (Fig. 52). However, in proportion to the accumulation of damage in the material when under conditions of creep tests is developed tertiary creep, the intensity of the processes of relaxation with repeated loadings increases without depending on the character or the cyclic instability of material.

Nevertheless most frequently with the repeated loadings of material it is strengthened. As the illustration of aforesaid can serve the data given in Table 12.

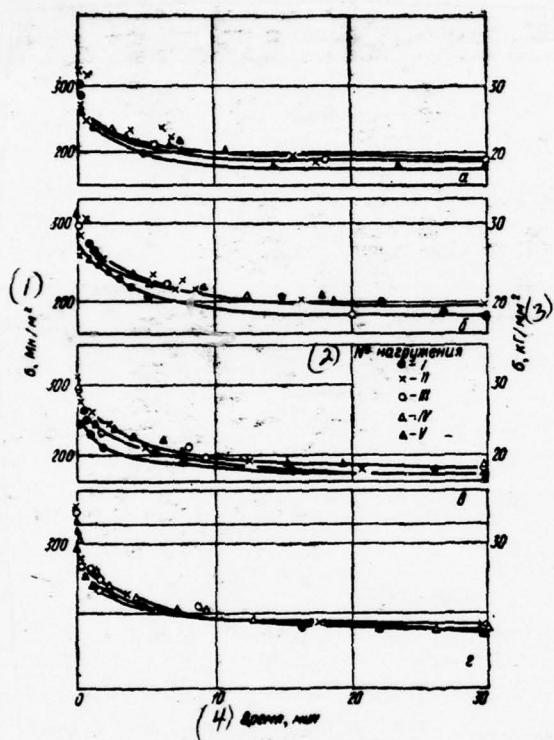


Fig. 52. Curves of the repeated relaxation of alloy EI827 at 900°C and σ_0 , MN/m² (kg/mm²): a) 320 (32); b) 350 (35); c) 370 (37); d) 400 (40).

Key: (1). MN/m². (2). Nc loading. (3). kg/mm². (4). Time, min.

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Table 12. Relaxation resistance of some materials with repeated pull
[76, 106].

(1) Материал	(2) Темпера- тура, °C	(3) Номер нагруже- ния	(4) $\sigma_{\text{н}}$, Мн/м ² (кг/мм ²)	$\sigma_t^{(5)}$, Мн/м ² (кг/мм ²), за время, ч				
				24	100	1000	1500	5000
20Х1М1Ф1Т (ЭП182)	565	1	250 (25)	—	201 (20,1)	—	—	—
		10			220 (22,0)	—	—	—
20Х1М1Ф1ТБ (ЭП188)	565	1	300 (30)	—	—	160 (16,0)	—	126 (12,55)
		2			—	178 (17,75)	—	140 (14,0)
	580	1	300 (30)	—	—	145 (14,5)	—	110 (11,0)
		2			—	164 (16,4)	—	135 (13,5)
20Х3Ф1ВМТ (ЭП189)	565	1	300 (30)	—	—	124 (12,35)	—	101 (10,1)
		2			—	152 (15,2)	—	119 (11,9)
	580	1	—	—	—	123 (12,3)	—	92,6 (9,2)
		2			—	158 (15,8)	—	127 (12,7)
Х18Н10Т	20	1	350 (35)	213 (21,3) 297 (29,7) 328 (32,8)	—	—	—	—
		2				—	—	—
		8				—	—	—
	150	1	350 (35)	270 (27,0) 309 (30,9) 334 (33,4)	—	—	—	—
		2				—	—	—
		8				—	—	—
	300	1	350 (35)	307 (30,7) 336 (33,6) 348 (34,8)	—	—	—	—
		2				—	—	—
		8				—	—	—
ХН70ВМЮТ (ЭИ765)	700	1	250 (25)	—	—	—	145 (14,5)	—
		2					200 (20)	—
	725	1	250 (25)	—	—	—	140 (14)	—
		2					175 (17,5)	—
		4					190 (19)	—

Key: (1). Material. (2). Temperature, °C. (3). Number of stress

applications. (4). MN/m² (kg/mm²). (5). MN/m² (kg/mm²), for time, h.

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This property can be used by decreasing the initial stresses in fastening for its repeated pull, which as a result will lead to an increase in its efficiency.

The ability of materials at the moderate temperatures to increase its relaxation life in the process of repeated stress applications finds another practical use: some parts are subjected the so-called "aging", which consists in preliminary strengthening of material via one or several repeated loadings of a comparatively small duration.

"training/aging" can be realize/accomplished under conditions of constant or alternating/variable temperature level and different duration of cycles. Stress application can be manufactured to value $\sigma_{0(n)}$ lower than initial stress ($\sigma_{0(n)} < \sigma_0$), equal to initial stress ($\sigma_{0(n)} = \sigma_0$) and higher than initial stress ($\sigma_{0(n)} > \sigma_0$).

As a rule, in each subsequent cycle strengthened/hardened effect $\sigma_{0(n)}$ is decreased, and after certain number of loadings either is reached constant value $\sigma_{0(n)}$, or the latter begins to be decreased.

In pearlitic steel this occurs usually after the third-fourth loadings [92, s. 87], in austenitic ones - already after the second-third [24].

On the whole the degree of the effectiveness of training/aging is determined by the combination of temperature, values of σ_0 and $\sigma_{0(n)}$, of number of insertions and by intervals between them. So large a number of factors impedes the establishment of general laws and the optimum conditions/modes of training/aging for separate steels and alloys, until now, they are selected experimentally.

Analytical dependences for relaxation with repeated loadings can be found within the framework of different hypotheses of creep.

Thus, for instance, as were shown on p. 3 of Chapter II, satisfactory conformity with experimental data was obtained according to the combination theory [1] for steel 25Kh2M1F, which was testing at 580°C (see Fig. 15).

The calculations of repeated relaxation according to the hypothesis of strengthening calculate a change in the creep rate in proportion to the accumulation of plastic deformation during the preceded cycles of relaxation.

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Within the framework of hypothesis, the decrease of the intensity of relaxation with repeated loadings is considered by changing (decrease) the creep rate for the time of the previous cyclic loadings.

As an example this calculation¹ was carried out in connection with tests for short-term relaxation of the alloy of KhN70VMuT.

FOOTNOTE¹. Was used the program of calculation, given in appendix.
ENDFOOTNOTE.

As can be seen from Fig. 53, the curves of relaxation for the second and subsequent loadings, the calculated by theory flows with the structural parameter, they coincided between themselves and they are characterized by the higher values σ_t in comparison with the remaining stresses with the first loading.

Stress relaxation for the cycles of the repeated loading, with

which is observed the softening of material, caused by its defectiveness, we can be described by equation [33, 110]

$$\dot{\varepsilon}_n = m(\varepsilon_n + \varepsilon_{ni})^{1-\alpha} \exp \left[\alpha (\sigma_{0i} - \gamma E \varepsilon_n) \frac{1 + k(\varepsilon_n + \varepsilon_{ni})}{1 + \gamma k(\varepsilon_n + \varepsilon_{ni})} \right], \quad (153)$$

where ε_{ni} - creep strain, accumulated in the previous cycles of relaxation; γ - rigidity of loading; σ_{0i} - initial stress with next loading, connected with the value of load by the relationship/ratio

$$[\sigma = \frac{P}{F_i} [1 + k(\varepsilon_n + \varepsilon_{ni})]]. \quad (153a)$$

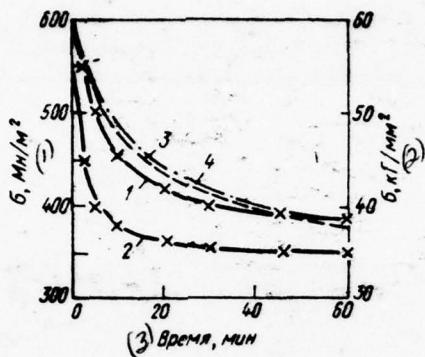


Fig. 53. The curves of the relaxation of the alloy of KhN70VMyUT with 750°C and $\sigma_0=600 \text{ MN/m}^2$ (60 kg/mm^2): 1, 2 - experimental; 3, 4 - calculated; 1, 3 - first loading; 2, 4 - second loading.

Key: (1). MN/m^2 . (2). kg/mm^2 . (3). Time, min.

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Here k - coefficient of damage which just as the constants of material α , m and n , depends on testing temperature.

2. Relaxation with alternating loading.

The laws governing cyclic relaxation with alternating stress can be established on the basis of the analysis of the behavior of materials under conditions of cyclic creep with alternating stress. Direct/straight experiments for relaxation under such

conditions, unfortunately in the literature are not described.

Tests for cyclic creep with alternating loading were conducted under conditions of elongation - compression [108] and twisting [111-113].

Under conditions of elongation - compression, experience/tested the alloys on the nickel basis of brands KhN70VMuT with 750°C and KhN70VMuT with 800°C. At these temperatures the materials indicated are structurally stable and, as showed the described below relaxation tests with repeated loads, cyclically they are softened.

Tests carried out during the symmetrical cycle of loading. The period of cycle was varied from 25 min to 48 h. Without depending on the sign of the stress in the first half cycle, creep strain, accumulated for the half cycle of elongation, exceeded creep strain for the half cycle of compression (to 15-25%).

However, during first 10-15 s of testing with the reversed load, reverse elastic after-effect after the removal of the load of opposite sign caused a noticeable increase in the initial velocity of creep (Fig. 54).

The results of some cyclic tests are given to Fig. 54-56 and in

Table 13.

From the examination of curves of cyclic creep evident that with an increase in the number of cycle accumulated for half cycle creep strain increases at first, and then it becomes constant. For the period of cycle 25 min, the curves of creep are stabilized beginning with the 15th cycle.

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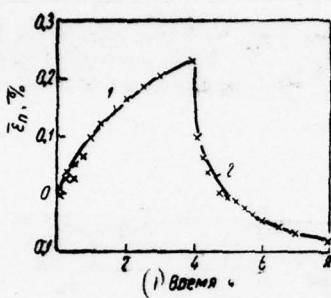


Fig. 54. Curve of alternating creep during first cycle of tests of alloy KhN70VMFTYu (EI826) at 800°C and $\sigma=20 \text{ MN/m}^2$ (20 kg/mm²): 1 - elongation; 2 - compression.

Key: (1). Time h.

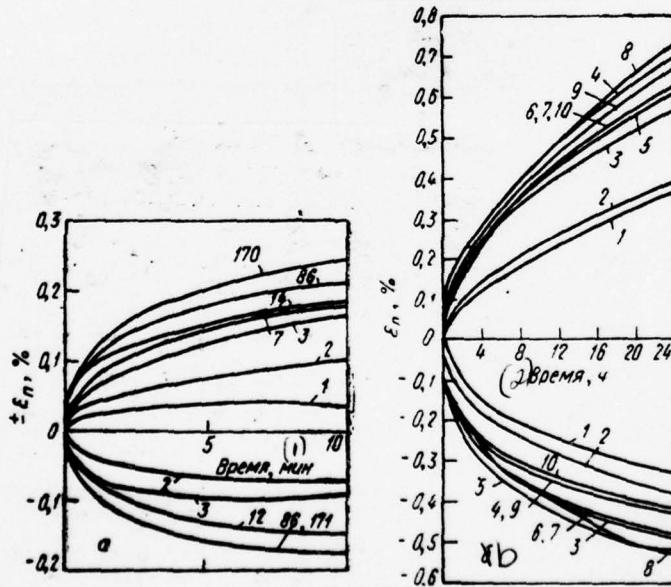


Fig. 55. Curves of creep during elongation and compression depending

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on number of cycle (they are shown in curves): a) - alloy to
KhN70VMFTYu with 800°C , $\sigma=300 \text{ MN/m}^2$ (30 kg/mm^2); b) - alloy
KhN70VMyuT with 750°C , $\epsilon=300 \text{ MN/m}^2$ (30 kg/mm^2).

Key: (1). Time, min. (2). Time, h.

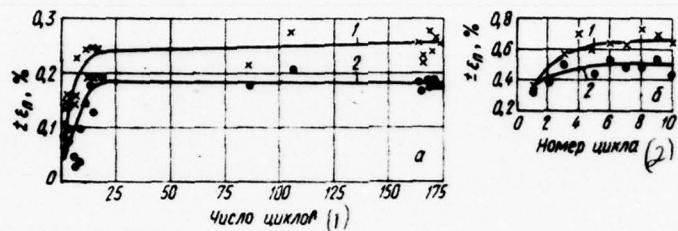


Fig. 56. The dependence of creep strain on a number of cycles: a) - alloy EI826 with 800°C, $\sigma=300 \text{ MN/m}^2$ (30 kg/mm²) for half cycle in tests under the conditions: 10 min elongation, 10 min compression; b) - alloy EI765 with 760°C, $\sigma=300 \text{ MN/m}^2$ (30 kg/mm²) for the half cycle of testing under the conditions: 24 h elongation, 24 h compression: 1 - elongation; 2 - compression.

Key: (1). Number of cycles. (2). Number of cycle.

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An increase in the period of cycle leads to the stabilization of curves of cyclic creep after a smaller number of cycles (3-5 cycles under conditions of tests with the period of 48 h). What is heavy-duty/critical for this behavior of the materials, tested with the different period of the cycle: the effect of frequency or a difference in the amounts of accumulated in cycle creep strain, at present to unambiguously establish/install.

The experiments conducted showed that the investigated materials at the selected temperatures appear as cyclically softened under conditions creeps with alternating loading just as under conditions of repeated relaxation.

Thus, and under conditions of the alternating loading of the characteristic of creep and, consequently, also relaxation is not stable ones. It is possible to assume that at the lower temperatures at nickel base alloys will be observed cyclic strengthening under conditions of alternating creep (relaxation).

Similar behavior of materials characteristically not only for nickel base alloys.

Table 13. Results of some tests for alternating creep.

Сплав (1)	Температура, °C (2)	σ		Период цикла (5)	Установившаяся деформация, %, полученной за цикл (6)		Число циклов N (9)	τ_p , ч (10)
		MН/м² (3)	кГ/мм² (4)		растяжение (7)	сжатие (8)		
ХН70ВМЮТ	750	250	25	48 4 (2)	0,6	0,5	3 (144)	
		300	30	48 4 (2)	0,65	0,5	10 (480)	
		400	40	25 мин (11)	0,11	0,07	127	53
ХН70ВМФЮ	800	300	30	25 мин (11)	0,24	0,18	178	74
		300	30	8 4 (10)	0,43	0,38	3	(24)

Note. In brackets is shown the time of testing the unexploded specimen/samples.

Key: (1). Alloy. (2). Temperature. (3). MN/m². (4). kg/mm². (5). Period of cycle. (6). Steady strain, o/o, creep in cycle. (7). elongation. (8). compression. (9). Number of cycles. (10). h. (11). min.

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Cyclic softening during alternating creep was revealed/detected in experiments with lead with 29°C [112], while cyclic strengthening in experiments for the cyclic twisting of copper with 230°C [111].

The examination of curves of cyclic creep (see Fig. 55, 56) makes it possible to accept assumption about their similarity for the half cycles of elongation and compression.

Then the amount of creep strain, accumulated for k-th half cycle, can be described with the aid of certain function of a number of cycles $f_2(k)$ as follows:

$$\epsilon_n^k = f_2(k) \epsilon_n^{(1)}. \quad (154)$$

Assuming that $f_2(k)$ does not depend on time, we have

$$\dot{\epsilon}_n^k = f_2(k) \dot{\epsilon}_n^{(1)}. \quad (154a)$$

Thus, by utilizing, for example, a hypothesis of strengthening, it is possible to calculate the characteristics of cyclic alternating relaxation. For the case of softening with the subsequent stabilization, was suggested following expression for $f_2(k)$:

$$f_2(k) = 1 + (m' - 1) [1 - \exp(-\alpha(k-1))], \quad (155)$$

While for the case of strengthening with the subsequent stabilization of curves of creep

$$f_2(k) = \frac{1}{m} + \left(1 - \frac{1}{m}\right) \frac{1}{k^\beta}, \quad (156)$$

where m' , m , α and β - the constants, depending on material, temperature and frequency of cycle.

Below corrected values of constants m' and α for the alloy of KhN70VMYuT with 750°C:

(1) Период цикла, ч	48	0,33
m'	1,8	4,0
α	0,52	0,10

Key: (1). Period of cycle, h.

In spite of the fact that with the decrease of the period of cycle the rate of increase m' , apparently, attenuates, for rough estimates it is possible to make the assumption that

$$\frac{m'_1}{m'_2} = \lg \left(\frac{\tau_{u_1}}{\tau_{u_2}} \right), \quad (157)$$

where τ_u - period of cycle.

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3. Relaxation during cyclic variation in the temperature.

One should distinguish the following conditions of stress relaxation at the variable temperature:

A - condition of the constancy of the length of specimen/sample, retained during change temperature.

B - condition of the compensation for the thermal expansion of specimen/sample by the thermal expansion of the elements of system.

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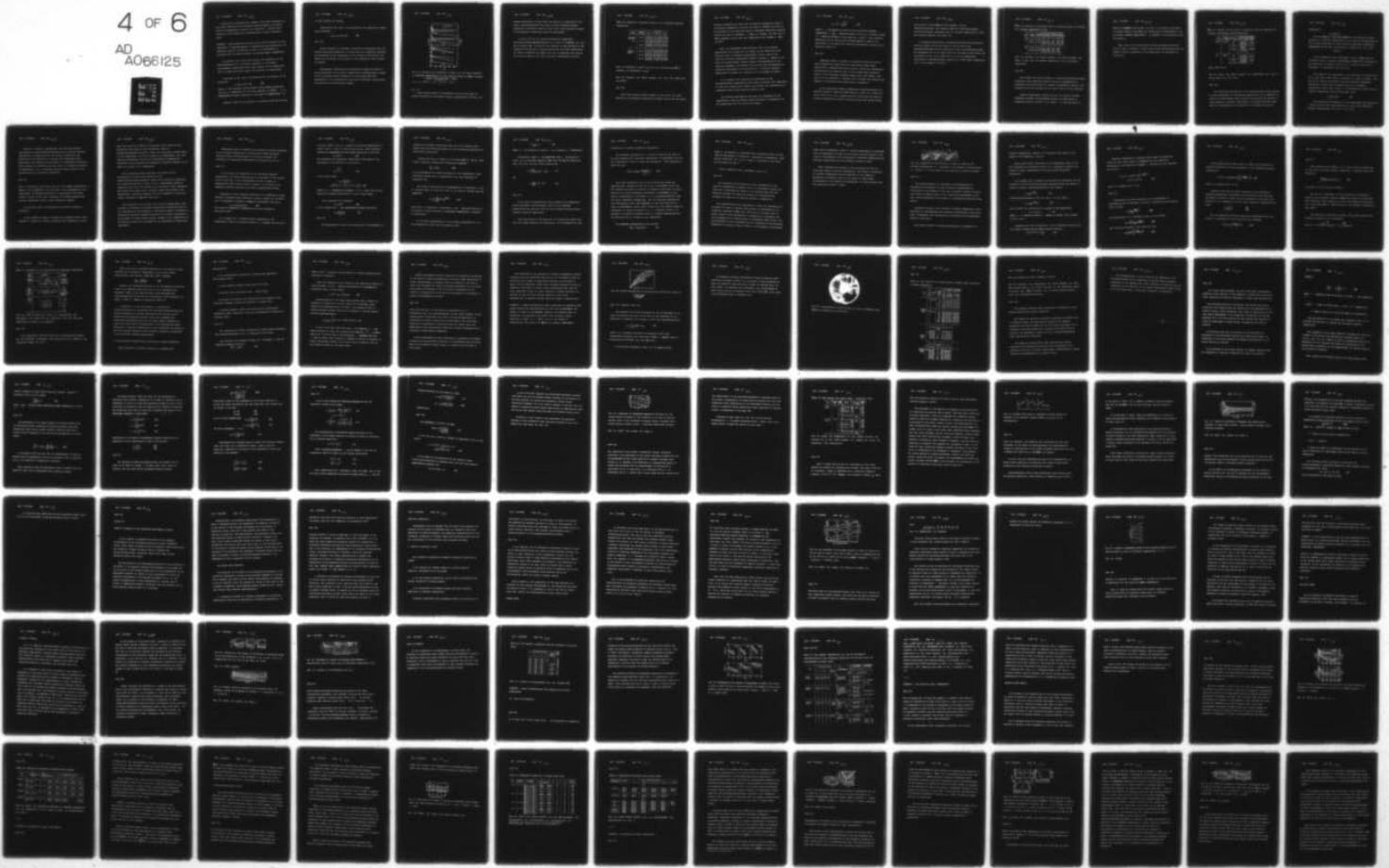
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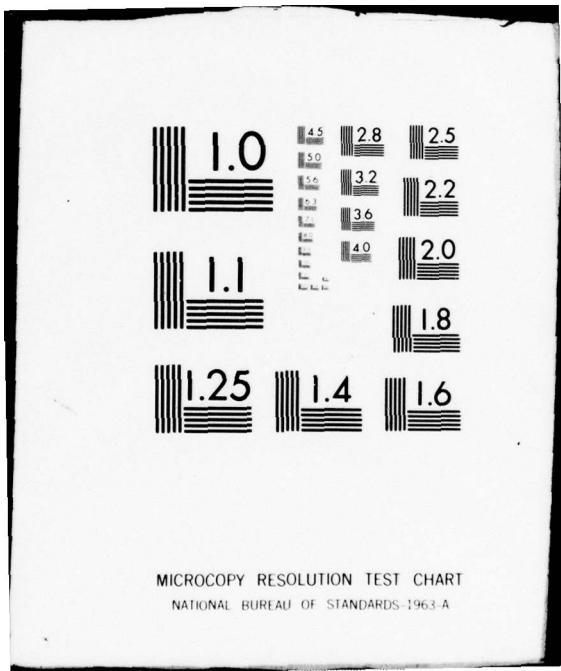
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Condition A is observed, for example, with rigid attachment in the cycled captures of the elongated specimen/sample, cyclically heated by transmission current¹, the condition B - during cyclic variation in the temperature simultaneously of entire fastening joint.

FOOTNOTE¹. Such conditions are also during cyclic variation in the temperature of specimen/sample in compensating type machines for the relaxation tests at elongation, in which the extensometer is connected with the working length of specimen/sample. ENDFOOTNOTE.

In practice, as a rule, were possible the conditions of the undercompensation for the thermal expansion of the loaded cell/elements, especially during rapid changes in the temperature when in system inevitably appear the gradients of temperatures.

Conditions of the type A are described by the equation of the relaxation

$$\epsilon_y + \epsilon_{nn} + \epsilon_n = A - \Delta t\alpha, \quad (158)$$

where A - the constant, which depends on the loading conditions, $\Delta t = t - t_{cp}$; t - temperature at the given instant, $t_{cp} = \frac{t_{max} + t_{min}}{2}$; α - a coefficient of linear expansion in the range of temperatures $t - t_{cp}$.

Equation (158) is the equation of relaxation with the changing

in time rigidity of loading.

Conditions of the type B are described by the equation of common type relaxation:

$$\epsilon_y + \epsilon_{nn} + \epsilon_n = \epsilon_0 = \text{const.} \quad (159)$$

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Stress relaxation at variable temperature is connected with the special feature/peculiarities of creep under the conditions indicated and dependence on the temperature of the modulus of elasticity. The latter can be brought to the effect of the changing in time rigidity of loading.

Considerable difficulties are encountered during the study of stress relaxation at the cyclic temperatures, bringing about a change in the structural state of material. In connection with this subsequently, let us examine only such test conditions, during which the materials are structurally stable.

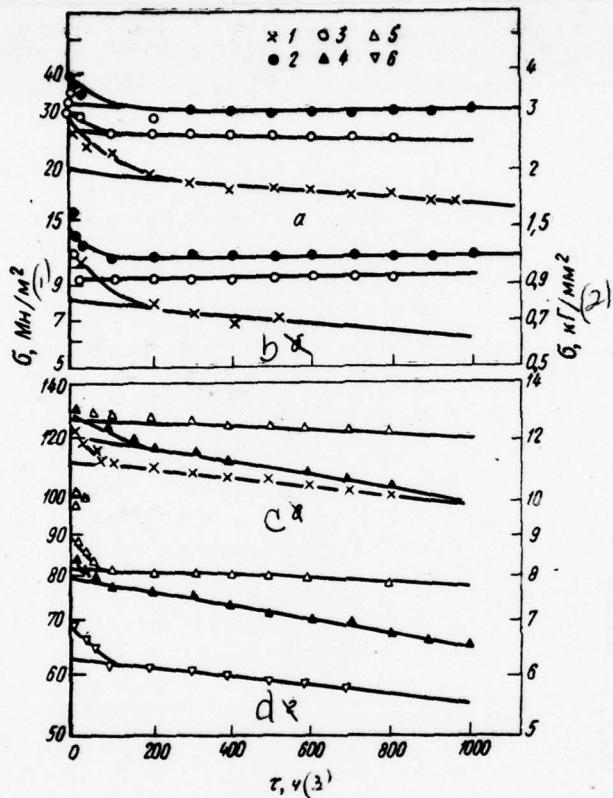


Fig. 57. Curves of the relaxation of ARMCO iron and steel Kh18Yu10T at different temperatures, °C, and initial stress σ_0 , MN/m² (kg/mm²):

a — 100(10); b — 30(3); c — 200(20); d — 100(10); 1 — 400—150° C;
2 — 400 = const; 3 — 450 = const; 4 — 575—625; 5 — 575 = const;
6 — 625 = const

Key: (1). MN/m². (2). kg/mm². (3). h.

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Known limited number of experimental works on the study of stress relaxation at cyclically changing temperatures [114-116]. The

loading conditions in these tests are related to conditions of the type B (experience/tested the rings of equal strength bending). Temperature cyclically changed on $\pm 25^\circ$ [116, 114]; therefore changes in the modulus of elasticity could be disregarded.

In work [116] at the cyclically changing temperature experience/tested specimen/samples IS or steel of Kh18N10T ($\tau_n=1$ h) and the ARMCO iron ($\tau_n=2.5$ h). The interval of the variation in the temperature was 50 deg on average levels 60°C and 425°C respectively for steel of Kh18N10T and ARMCO iron. For a comparison were carried out also the tests at the upper and lower temperatures of cycle.

Table 14. Results of relaxation tests at the cyclically changing temperature.

Material (1)	$\sigma_0, \text{Mn/mm}^2$ (kg/mm ²) (2)	$\Delta\sigma$ при (3)		
		t_{\min}	t_{\max}	$t_{\text{цикл}}$
Армко-железо (при 600°C) (4)	100 (10)	69 (6,9) 70,3 (7,03)	73,4 (7,34) 76,4 (7,64)	81,8 (8,18) 85,5 (8,55)
	70 (7)	46,1 (4,61) 47,3 (4,73)	52,4 (5,24) 53,4 (5,34)	48,1 (4,81) 51,6 (5,16)
	30 (3)	19,4 (1,94) 19,4 (1,94)	21 (2,10) 21,4 (2,14)	22 (2,20) 23,7 (2,37)
Х18Н10Т (при 425°C) (3)	200 (20)	71,7 (7,17) 78,7 (7,87)	88,6 (8,86) 101,6 (10,16)	75,9 (7,59) 99,9 (9,99)
	150 (15)	36,1 (3,61) 42,1 (4,21)	62,9 (6,29) 69,8 (6,98)	45,5 (4,55) 62,1 (6,21)
	100 (10)	19 (1,90) 22,4 (2,24)	38,1 (3,81) 45 (4,5)	21,9 (2,19) 34,4 (3,44)

Note. In numerator is shown a drop in the voltage $\Delta\sigma_{1000}$, Mn/mm^2 (kg/mm^2), in denominator $\Delta\sigma_{1000}$.

Key: (1). Material. (2). Mn/mm^2 (kg/mm^2). (3). with. (4). ARMCO iron (at 600°C).

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Basic test results, given in Table 14 and to Fig. 57, show following: the relaxation resistance of ARMCO iron at the cyclically

changing temperature is less than at constant temperature, equal to the maximum temperature of cycle. For steel of Kh18N9T, the rate of the decrease of the remaining stress at variable temperature somewhat exceeds the rate of reduction σ_r when t_{max} ; however, for the time of 1000 h residual stress when t_{max} everything still exceeds σ_r , when $t_{max} = \text{const.}$

Thus, the experiments conducted show that if at constant temperatures the voltage drop in essence occurs during the first stage and then it increases comparatively slowly, then at the cyclically changing temperatures intense decrease σ_r occurs at the first and second stages. Without offering explanation of to the occurring phenomena, the authors [116] assume that the decrease of relaxation resistance at the second stage of tests at variable temperatures is caused by a decrease in the strength of grains.

E. K. Gordeev [114] carried out experiments in the specimen/samples, manufactured from steels 40 and U8. The temperature of tests was varied within limits of 400-450°C. The oscillations of temperature during tests did not exceed 50 deg.

The obtained experimental test data for relaxation at the temperatures, which cyclically change according to triangular law, are generalized with the aid of the formula

$$\sigma_p = \sigma_0 \left(1 - \frac{1 - \frac{\sigma_t}{\sigma_0}}{\rho^{a+b\rho}} \right), \quad (160)$$

where σ_p - the remaining stress at the cyclically changing temperature; $\rho = \frac{t_{min}}{t_{max}}$ - characteristic of cycle; σ_0 - initial stress; σ_t - remaining stress in tests when t_{max} ; a and b - the constants, determined for the arbitrarily selected moment of time of two experiments at the cyclically changing temperatures, carried out at different values t_{min} .

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Dependence (160) is obtained in connection with the form of cycle accepted and generalizes the experimental data, which characterize a comparatively narrow range ρ (0.9-1.0). Furthermore, when deriving the equation (160) it was assumed that relaxation curves at the cyclically changing temperatures were similar, that also it is not possible to consider the as general law governing the behavior of materials under conditions of relaxation.

At the cyclically changing temperatures experience/tested the pearlitic steel of 12Mk and 15KhM [115] (at 425°C 12 h, 450°C 20 h and at 475°C 16 h). For a comparison were carried out the tests at constant temperature of 450°C. Initial stresses were varied within

the limits of 100-230 M_i/mm^2 (10-23 kg/mm²). It was established/installation, that stopped 12MKh and 15KtM they possess virtually identical relaxation life at constant temperature of 450°C and variable $450 \pm 25^\circ C$ (see Table 15).

At variable temperatures is experience/tested also reinforcing wire [58] whose cuts by the length of 200 mm fed to the assigned/prescribed initial voltage with 20°C and experience/tested for relaxation for 2-4 h, after which was switched on the furnace and was heated to 100, 175 or 200°C for 4 h. At the temperatures indicated the specimen/samples age/held 10 h, after which temperature for 4 h they reduced to 20 deg.

Table 15. Results of relaxation tests of pearlitic steel at constant and variable temperatures [115].

Мате- риал (1)	$\sigma_0, \text{МН/м}^2$ ($\text{kг}/\text{мм}^2$) (2)	$\sigma_t, \text{МН/м}^2$ ($\text{kг}/\text{мм}^2$), за время, ч, при (3)					
		постоянной температуре (4)			переменной температуре (5)		
		500	1250	1700	500	1250	1650
12MX	160 (16)	116 (11.6)	113 (11.3)	111 (11.1)	115 (11.5)	104 (10.4)	103 (10.3)
	200 (20)	127 (12.7)	123 (12.3)	122 (12.2)	133 (13.3)	122 (12.2)	122 (12.2)
15XM	160 (16)	122 (12.2)	115 (11.5)	112 (11.2)	108 (10.8)	105 (10.5)	—
	200 (200)	149 (14.9)	140 (14.0)	135 (13.5)	130 (13.0)	125 (12.5)	—

Key: (1). Material. (2). MN/m^2 (kg/mm^2). (3). MN/m^2 (kg/mm^2), for time, h, with. (4). To constant temperature. (5). to variable temperature.

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Test results are given in Table 16. Established/installation sharp reduction in the remaining stress at variable temperatures in comparison with those tested at constant temperatures. However, any explanation of this behavior by the author [58] he is not proposed.

Separate experiments carried out with the alloys of brands KhN80TBYuA (EI607A) and KhN70VMYuT (EI765) on nickel basis at temperature cycle of 700°C, 7 h + 750°C, 1, h. For the alloy of

EI607A $\sigma_0=200 \text{ MN/m}^2$ (20 kg/mm²) for 1600 h it relaxed to 100 mN/m^2 (10 kg/mm²) when t_{\min} and when t_{\max} . In the alloy of KhN70VMYut at the cyclically changing temperature σ_t it proved to be considerably less than when t_{\min} .

Thus, that is the sufficiently limited experimental material does not make it possible to make single-valued conclusions about the effect of cyclic variations in the temperature for resistance of relaxation.

Table 16. Results of the tests of reinforcing wire for relaxation at constant and variable temperatures [58].

Сталь (1)	$\sigma_0, \text{МН/м}^2 (\text{кг}/\text{мм}^2)$ (2)	Температура, °C (3)	Потеря напряжения за 22 с (4)	
			$\text{МН/м}^2 (\text{кг}/\text{мм}^2)$ (5)	% (6)
20ХГ2Ц	500 (50)	20	25 (2,5*)	5,0*
		100	46,5—48,8 (4,65—4,88)	9,3—9,75
		20—100—20	73,4—91 (7,34—9,1)	14,7—18,2
		175	100 (10)	20
		20—175—20	113—142,5 (11,3—14,25)	22,6—28,4
80С	600 (60)	20	5,5 (0,55)*	1,1*
		100	31,7—32,2 (3,17—3,22)	5,28—5,37
		20—100—20	119,3 (11,93)	19,9
		175	42—48,5 (4,2—4,85)	7,0—8,1
		20—175—20	162 (16,2)	27,0

Note: after 100 h.

Key: (1). Steel. (2). $\text{МН/м}^2 (\text{kg}/\text{mm}^2)$. (3). Temperature. (4). Loss of stress after 22 h. (5). frcs.

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For analytical determining of the characteristics of the process of stress relaxation at the changing temperature, it is expedient to utilize the same methods which apply for description and forecast of creep strength at variable temperatures. In general form the creep rate can be presented as the function of the stress of time and

temperature:

$$\dot{\epsilon}_n = \dot{\epsilon}_n(\sigma, t, \tau).$$

Let us examine at first the methods of calculation of stress relaxation at variable temperatures on the basis of the conditions of the constant velocities of creep with the appropriate temperature step/stages of the cycle (see Section 2, Chapter II), i.e., when

$$\dot{\epsilon}_n = \dot{\epsilon}_n(\sigma, t).$$

Stress relaxation under conditions $\dot{\epsilon}_n = \dot{\epsilon}_n(\sigma, t)$. Widest use for describing creep at variable temperatures received the hypothesis of the additivity of strains [117], that is a special case of the hypothesis of transformed time [27, 118].

The essence of the hypothesis of the additivity of strains lies in the fact that creep strain, accumulated in cycle, is equal to the sum of the strains, accumulated with the different temperature step/stages of cycle and calculated from data at constant temperatures. Thus, creep strain ϵ_n is determined by creep rates at constant temperatures and by form of the cycle:

$$\epsilon_n = \int_0^t \dot{\epsilon}_n[t(\tau)] d\tau. \quad (161)$$

The experimental confirmation of this hypothesis was obtained in a whole series of the investigations of creep at the cyclically changing temperatures [117, 119, s. 117; 120].

However, in series of experiments [121-126] was observed acceleration or retarding/deceleration/delay of creep at variable temperatures in comparison with the values, predicted by the hypothesis of the additivity of strains. For explaining these differences, was advanced the hypothesis of temperature aftereffect, which consists in following: any real solid is hereditary according to temperature, i.e., it possesses peculiar memory system in the ratio/relation to temperature prehistory.

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This, in particular, means that with any, for example intermittent, a change in the temperature the creep rate, which corresponds to new temperature, is established not immediately, but during certain interval of the time, necessary for "memory system" about previous temperature would be being completely removed.

The physical nature of temperature aftereffect consists in following.

In the process of creep, is formed the structural state, which depends on a number of factors, including from temperature. At the

same time creep rate depends on structural state. Since at each temperature new stable at this temperature state is establish/installed gradually in time, and creep rate, characteristic for new temperature, it will be acquired not immediately, that also indicates aftereffect. The use of a hypothesis of temperature aftereffect can be advisable for materials structural unstable in the range of a change in the temperature.

For structurally stable materials the effects of the acceleration of creep during heating and the retarding/deceleration/delays of creep during cooling in comparison with predicted equation of state can to a considerable degree be compensated for [27]. For testing of the validity of this assumption, were carried out creep tests of several nickel base alloys at the temperatures, cyclically changing with high frequency (3 cycles per minute) according to saw-tooth law [127].

The comparison of the values of the rate of steady-state creep conducted at constant and variable temperatures showed that the use of a hypothesis of the additivity of deformation makes it possible to sufficiently correctly describe obtained test results. Consequently, the processes of creep during frequent changes in the temperature can be described without the enlistment of the hypothesis of temperature aftereffect.

Subsequently will be examined the processes of stress relaxation at the variable temperatures in structurally stable materials. Therefore during the development of calculated methods, the hypothesis of temperature aftereffect be utilized will not be.

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In the process of relaxation at the cyclically changing temperatures, one should distinguish two conditions: 1) the voltage drop for the time, to the corresponding period of cycle, is comparatively small (short period of cycle); 2) a change in the temperature during relaxation test occurs comparatively slowly.

Depending on test conditions indicated it is expedient to apply different approaches when selecting of design diagram. In the first case is expedient to utilize a concept of equivalent creep rate:

$$\dot{\epsilon}_{n,s} = F\{t(\tau), \dot{\epsilon}_n[\sigma, t(\tau)]\}, \quad (162)$$

that making it possible to determine the course averaged of relaxation curve.

As an example let us examine stress relaxation at the temperatures, which are changed according to triangular law ($t=t_1+\alpha\tau$,

$t=t_2-\beta\tau$), where t_1 and t_2 - minimum and maximum temperatures of cycle; α and β - rate of heating and cooling. After accepting temperature dependence for the steady creep rate in the form

$$\dot{\varepsilon}_n = Ae^{-B/T} \quad (163)$$

and expression for equivalent creep rate on the basis of the hypothesis of the addition of the strains

$$\dot{\varepsilon}_{ns} = \frac{\int_0^{\tau} \dot{\varepsilon}_n d\tau}{\tau}, \quad (164)$$

we will obtain [29]

$$\begin{aligned} \dot{\varepsilon}_{ns} &= \frac{T_2 \dot{\varepsilon}_{n2} - T_1 \dot{\varepsilon}_{n1}}{T_2 - T_1} - \\ &- \frac{AB}{T_2 - T_1} \left[\left\{ -E_i\left(-\frac{B}{T_2}\right) \right\} - \left\{ -E_i\left(-\frac{B}{T_1}\right) \right\} \right], \end{aligned} \quad (165)$$

where $E_i(-x)$ - exponential integral; $\dot{\varepsilon}_{n1}$, $\dot{\varepsilon}_{n2}$ - creep rate at the minimum and maximum temperatures of cycle respectively.

After accepting the dependence

$$\dot{\varepsilon}_n = A_1 e^{B_1 T}, \quad (166)$$

we will obtain for $\dot{\varepsilon}_{ns}$ the considerably simpler expression

$$\dot{\varepsilon}_{ns} = \frac{\dot{\varepsilon}_{n2} - \dot{\varepsilon}_{n1}}{B_1(T_2 - T_1)}. \quad (167)$$

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The experimental check of the possibility of calculation $\dot{\varepsilon}_{ns}$

conducted at variable temperature with the aid of formula (167) showed that the accuracy/precision of such calculated evaluations is sufficiently high [128].

Knowing the law of a change in the creep rates $\dot{\epsilon}_{n_1}$ and $\dot{\epsilon}_{n_2}$ from stress, possible, deciding the differential equation

$$\frac{d\sigma}{dt} = -E_s \dot{\epsilon}_{n_{1,2}}, \quad (168)$$

to find dependence for stress relaxation at the temperature, which cyclically changes with a comparatively high rate according to triangular law.

The value of the equivalent module/modulus of elasticity E_s can be accepted equal to value of E when t_{cp} of cycle or refined from the dependence

$$E_s = \left[\frac{1}{\tau_u} \sum_{i=1}^k E_i^{n_i(T)} \Delta \tau \right]^{\frac{1}{n(t_{cp})}}, \quad (169)$$

where $n(T)$ - an exponent of expression $\dot{\epsilon}_n = M \sigma^n$ (slope/inclination of the curves of creep strength in logarithmic coordinates), depending on temperature.

In the first approximation, can be accepted dependence of n on the temperature in the form of expression (32):

$$n = \frac{\gamma_0}{RT} + C, \quad (170)$$

where γ_0 - an activation volume; R - gas constant; T - temperature.

Disregarding value ε_{n_i} in comparison with ε_n , in expression (167), let us integrate equation (168) with the use of expressions (51a) and (51b). We will obtain respectively

$$\tau = \frac{B_1 \Delta T}{(l-1) A E_s} \left(\frac{1}{\sigma^{l-1}} - \frac{1}{\sigma_0^{l-1}} \right) \quad (171)$$

and

$$\tau = \frac{B_1 \Delta T}{k B E_s} (e^{-k\sigma} - e^{-k\sigma_0}). \quad (172)$$

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In the case of comparatively slow changes in the temperature during relaxation tests relaxation curve can be designed consecutively for sections with the these differing little within sections values of temperature.

Since the values of the creep rate of material are known only with the limited quantity of temperatures, it is necessary for such

calculations to utilize parametric dependences.

The parameter, proposed by V. I. Nikitin [130] on the basis of two well matching with experiment dependences: cf exponential for the rate steady-state creep on stress and exponential - from temperature, takes the form

$$P(\sigma) = c + d \lg \sigma = \frac{\lg \dot{\epsilon}_n(\sigma, t) + a}{\frac{1}{T} + b}. \quad (173)$$

The linear dependence $E(\sigma)$ on the logarithm of stress was experimentally demonstrated for the alloy of KhN75VMFYu [130]. Was also checked the method of Nikitin in connection with data on creep, obtained for alloys KhN80TBYuA, KhN70VMYuT to KhN70VMFTYu in the range of temperatures of 600-850°C. It is established, that the linear dependence between $\log \dot{\epsilon}_n$ and $1/T$ describes sufficiently well experimental data, with exception of data with 600°C for an alloy to KhN70VMFTYu. Hence, after finding from the limited number of experiments to creep of constant a , b , c , d equation (173), it is possible to calculate relaxation curve at variable temperatures for the arbitrary law of a change in the temperature.

The numerical integration of the equation

$$\frac{d\sigma}{d\tau} = -E_{I(\tau)} \dot{\epsilon}_n[t(\tau), \sigma], \quad (174)$$

where ε_u is accepted in accordance with expression (173), and the value of the modulus of elasticity - depending on temperature, under initial conditions $\tau=0$, $\sigma=\sigma_0$, it makes it possible to find value for any moment of time τ .

Stress relaxation under conditions $\dot{\varepsilon}_u = \dot{\varepsilon}_u(\sigma, t, \tau)$.

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For describing the processes of creep (relaxation) at the variable temperatures in general form it is necessary to apply the other one or hypothesis of creep (it is analogous with that how different theories of creep were utilized for describing the processes of creep for the varying stresses in Chapter II).

The application/use of a hypothesis of aging for describing the processes of creep at variable temperatures is illustrated by the schematic, presented in Fig. 58b, from which it is clear that an abrupt change in the temperature is accompanied in accordance with this hypothesis by an abrupt change in accumulated creep strain. The groundlessness of this hypothesis for the conditions of the decreased temperature is obvious, since it leads to the decrease of accumulated

creep strain. Relaxation curves at variable temperature in accordance with the hypothesis of aging can be obtained from the curves of the creep of the material, which correspond to different temperatures and stresses consecutively for the different moments of time.

After accepting the validity of the hypothesis of flow for describing creep at variable temperatures, the curves of relaxation at variable temperatures can be calculated by the numerical integration of equation (49) for the values of creep rates, corresponding to the specific torque/moment of time and found from the appropriate curves of creep.

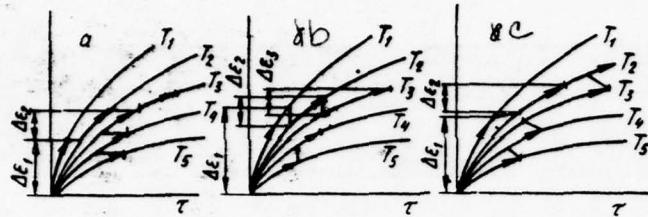


Fig. 58. Schematics of the plotting of curves of creep at the variable temperatures: a) - according to the theory of strengthening; b) - aging; c) - on the basis of the principle of relative strains.

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The application/use of a hypothesis of strengthening for describing the processes of creep at variable temperatures is illustrated by the diagram in Fig. 58a, according to which the creep rate during an abrupt change in the temperature corresponds to the rate, which corresponds to the amount of accumulated previously creep strain.

Relaxation curves at the cyclically changing temperature on the hypothesis of strengthening are calculated consecutively, cycle after cycle, introducing into the equation of relaxation the corresponding values of creep rate.

The graphic methods of curved determination of relaxation at

variable temperatures, however, are acceptable only during a slow change in the temperature (case 2).

During rapid cyclic variations in the temperature (case 1) for the calculation of relaxation curves it is expedient to utilize the curves of creep, approximated by the appropriate analytical expressions.

As an example let us examine the equations of relaxation for the conditions of the cyclically changing temperature when the family of curves of creep is assigned/prescribed by the formula

$$\sigma_n = A(\sigma) e^{-\frac{Q(\sigma)}{kT}} \tau^\alpha. \quad (175)$$

Differentiating equation (175) for time τ , we will obtain

$$\dot{\sigma}_n = \alpha A(\sigma) e^{-\frac{Q(\sigma)}{kT}} \tau^{\alpha-1}. \quad (176)$$

Let us accept the periodicity of a change in the temperature

$$T(\tau) = T(\tau + i\tau_u), \quad (177)$$

where τ_u - a period of cycle; i - number of cycles, which changes from 0 to N_0-1 .

Expression for the calculation of stress relaxation according to the theory of aging can be found from the equation

$$A(\sigma) e^{-Q(\sigma)/kT(\tau)} \tau^\alpha = \frac{\sigma_0 - \sigma}{E_s}. \quad (178)$$

Numerical integration of equation (168) under the conditions (176) and (177) gives system of equations for the consecutive calculation of the remaining stresses σ^i according to the hypothesis of the flow:

$$\sigma^{(i)} = \sigma^{(i-1)} - E_s \alpha A(\sigma^{(i-1)}) \int_0^{\tau_u} e^{-\frac{Q(\sigma^{(i-1)})}{kT(\tau)}} \times \\ \times [\tau + (i-1)\tau_u]^{\alpha-1} d\tau, \quad (179)$$

where i is changed from 1 to N_0 .

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Expressions for stress relaxation on the hypothesis of strengthening can be obtained as follows. Eliminating from condition (175) the time

$$\tau = \left[\frac{e_n}{A(\sigma)} e^{-\frac{Q(\sigma)}{kT}} \right]^{1/\alpha} \quad (180)$$

and substituting it in expression (176), we will obtain

$$\dot{\epsilon}_n = \alpha \epsilon_n^{\frac{\alpha-1}{\alpha}} \left[A(\sigma) e^{-\frac{Q(\sigma)}{kT(\tau)}} \right]^{1/\alpha}. \quad (181)$$

The solution of equation (181) takes the form

$$\epsilon_n = A(\sigma) \epsilon_n^\alpha \left[\int_0^{\tau_u} e^{-\frac{Q(\sigma)}{kT(\tau)}} d\tau \right]^\alpha. \quad (182)$$

After substituting formula (182) in (168), we will obtain the system of equations of stress relaxation at the cyclically changing temperature:

$$\sigma^{(i)} = \sigma^{(i-1)} - E_s \alpha A [\sigma^{(i-1)}] i^\alpha \left[\int_0^{\tau_u} e^{-\frac{Q(\sigma)(i-1)}{\alpha k T(\tau)}} d\tau \right]^\alpha, \quad (183)$$

where i is changed from 1 to N_0 .

Solving of the task of stress relaxation at the cyclically changing temperatures considerably is facilitated in the case when the family of curves of creep can be represented in the form of the function of a θ - parameter, in turn, which depends on temperature and time:

$$\varepsilon_n = \varepsilon_n(\theta, \sigma), \quad (184)$$

$$\theta = \theta(T, \tau). \quad (185)$$

For the alternating/variable temperature conditions $T=T(\tau)$ the value of a θ -parameter can be found from the expression

$$\theta [T(\tau), \tau] = \int_0^\tau \frac{\partial \theta [T(x), x]}{\partial x} dx. \quad (186)$$

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After equating value $\theta[T(\tau), \tau]$ to value θ for the same value of time, but at certain constant temperature T_0 , we will obtain the expression

$$\int_0^{T_0} \frac{\partial \theta [T(x), x]}{\partial x} dx = \theta [T_0, \tau_u], \quad (187)$$

from which we can be obtained value T_0 .

The use of a θ -parameter for the calculation of relaxation curves at the cyclically changing temperature lies in the fact that into expression (168) instead of $\dot{\varepsilon}_{u,0}$ are substituted the expression for a creep rate when T_0 , and the value of the modulus of elasticity also when T_0 .

This method was developed by Mandrel [131], which proposed the following expression for θ - parameter:

$$\theta = \tau e^{-\frac{U_0}{RT}}, \quad (188)$$

where U_0 - activation energy; R - gas constant.

Table 17. Formulas for the calculations of equivalent temperature.

Вид цикла (1)	(2) Значение T_e	Обозначения (3)
Прямоугольный (4)	$T_e = \frac{U_0/R}{\ln \frac{\tau_1 + \tau_2}{\tau_1 \exp\left(-\frac{U_0}{RT_1}\right) + \tau_2 \exp\left(-\frac{U_0}{RT_2}\right)}}$	τ_1 —время при T_1 ; (5) τ_2 —время при T_2 (5)
Синусоидальный (6) ($\frac{\Delta T}{T_0} < 1$)	$T_e = \frac{1}{T_0 - \frac{R}{U_0} \ln \sum_{n=1}^{\infty} \frac{2}{(2n)!} \frac{1}{2^{2n}} \binom{2n}{n} \lambda^{2n}}$	$\lambda = \frac{U_0 \Delta T}{RT_0^2}$; T_0 —средняя температура цикла (8)
Треугольный (9)	$T_e = \frac{A}{\ln \left\{ \frac{1}{\frac{A}{B} \int_l^k \frac{e^x}{x^2} dx} \right\}}$	$A = -\frac{U_0}{R}$; $B = T_1 - T_2$; $k = \frac{A}{T_1}$; $l = \frac{A}{T_2}$

Key: (1). Form of cycle. (2). Value. (3). Designations. (4). Rectangular. (5). time with. (6). Sinusoidal. (7). for. (8). mean temperature of cycle. (9). Triangular.

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From expressions (187) and (188) can be calculated the values for the sinusoidal, rectangular and triangular law of a change in the temperature (Table 17) [27].

Value U_0/R can be determined according to two curves to creep, obtained for two values of temperature T_1 and T_2 at $\sigma=\text{const}$. Real/actually, from equation (188) for $\varepsilon_n=\text{const}$ we have

$$-\frac{U_0}{RT} = \frac{\ln \tau_2/\tau_1}{1/T_2 - 1/T_1}. \quad (189)$$

However, the competence/validity of the description of curves of creep at the unsteady stage with the aid of θ - parameter from expression (188) is not always correct, which decreases the accuracy/precision of use for the calculations of the relaxation of value ε_n when T_n found from formulas by Table 17.

At present it is not the possible to estimate the accuracy/precision of determining the resistance characteristics of stress relaxation at variable temperatures with the aid of the examined above analytical methods, since such necessary for evaluations experimental data are virtually absent. Observing in works [114] and [116] the acceleration of the processes of stress relaxation at variable temperatures can be explained on the basis of the more detailed analyses of the structural stability of materials at the cyclically changing temperatures.

4. Stress-rupture strength under conditions of stress relaxation.

Under conditions of stress relaxation, is possible the

decomposition:

- a) in low-plasticity materials in uniaxial and especially multistressed state.
- b) with repeated constant loads (pull) [132-134].
- c) during cyclic relaxation tests - creep [135].
- d) during an increase in the stresses in part because of the structural changes, calling the decrease of volume [136].
- e) during repeated elastic and elasto-plastic alternating deformation under conditions, which are accompanied by relaxation of stresses [137].

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The conditions of brittle decomposition during stress relaxation were established in L. M. Kachanova's work [138].

Was utilized the dependence between the continuity Ψ and the effective stress in the form

$$\frac{d\Psi}{d\tau} = -A \left(\frac{\sigma}{\Psi} \right)^n, \quad (190)$$

where A and n - constants with constants to testing temperature and structure of material.

Under the condition of the absence in the material of damages at initial moment $\tau=0$, $\Psi=1$. During decomposition $\Psi=0$. Integrating expression (190), we will obtain

$$1 - \Psi^{n+1} = A(n+1) \int_0^{\tau} \sigma^n(\tau) d\tau. \quad (191)$$

Substituting for σ its value from equation (68), brought out according to theory flow, we will obtain the expression, which connects the characteristics of creep in the course of time of brittle delayed fracture during the relaxation (τ_r) of the rigidly attached specimen/sample:

$$\frac{1}{(n+1) A \sigma_0^n} = \int_0^{\tau_r} \sigma_0^n [1 + (m-1) E \sigma_0^{m-1} \Omega_1(\tau)]^{\frac{n}{1-m}} d\tau. \quad (192)$$

In view of the fact that with large τ the function Ω_1 - the linear function of time, the integrand diminishes as $\tau^{\frac{-n}{m-1}}$. If $n < m-1$, then there is finite time of decomposition τ_r ; otherwise the root τ_r can not exist. Then presence or absence of root it is possible to judge, calculating integral in the right side of equation (192) at the different values of the upper limit.

Brittle decomposition under conditions of relaxation is possible in the case of a small deformability of material under conditions of creep. Real/actually, if material with an increase in the time of creep test decreases the value of prolonged plasticity to 0.2-0.4%, then during the decrease of initial elastic deformation in the process of relaxation test for the value indicated it is possible to expect the decomposition of part.

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Along with the fact, as was shown in experiences in A. V. Stanyukovich with the specimen/samples, having spiral notches, stress concentrators is decreased the value of prolonged plasticity, in consequence of which in parts with concentrators, that work under conditions of relaxation of stresses (stud pin, bolts, etc.) and manufactured from low-plasticity materials, brittle decomposition is encountered comparatively frequently.

Brittle decomposition under conditions of relaxation of stresses of parts from low-plasticity materials is encountered also with other forms of the complex stressed state, for example with the bend of wide plates.

The conditions of the emergence of brittle decomposition during relaxation can be illustrated with the aid of the graphic method of the plotting of curves of relaxation according to the theory of aging. For the materials, which lower prolonged plasticity during an increase in the basis of tests, curved deformations they take the form, presented in Fig. 59. After conducting upright projection of diagram, we see that with initial stresses σ_1 and σ_2 the decomposition is possible through 25000 and 120,000 h respectively¹.

FOOTNOTE 1. Similar decomposition under conditions of relaxation with single loading was revealed/detected at 600°C and $\sigma_0=6000 \text{ MN/m}^2$ (60 kg/mm²) in steel of 4Kh18N8G8MFB (EI481), heat-treated under the conditions: the quenching with 1140°C with cooling in water, tempering at 670°C, 16 h + 720°C, 12 h. At the moment of decomposition (for 12 h) $\sigma_t=480 \text{ MN/m}^2$ (48 kg/mm²). ENDFOOTNOTE.

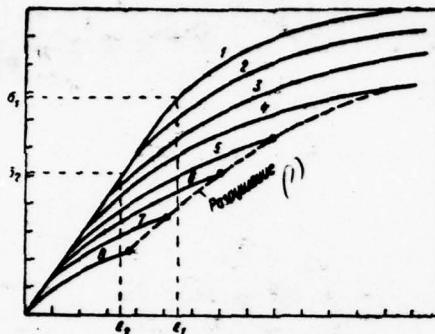


Fig. 59. Curved deformations of low-plasticity material for time, h:

1 - 0; 2 - 10; 3 - 100;
4 - 1000; 5 - 5000;
6 - 10000; 7 - 50000;
8 - 100000;

Key: (1). fracture. Page 181.

The condition of brittle decomposition can be described on the basis of strength criteria, on the basis of the principle of the additivity of damages. If we accept as valid the relationship/ratio

$$\sigma_s = \left[\frac{1}{\tau} \int_0^t \sigma^n d\tau \right]^{1/n} = \sigma_{\text{max},n}, \quad (193)$$

where σ it is changed according to relaxation curve, then decomposition possibly when equivalent stress σ_s becomes equal to stress-rupture strength $\sigma_{\text{max},n}$ the same time.

In more detail dependence (193) will be examined below.

As examples of brittle decomposition during relaxation under conditions of single loading, it is possible to give decomposition along the thread of stud pins made of steel of 25Kh1MFA (Fig. 60) after 12000 h of operation with 480-500°C, flat springs (state of plane stress $\sigma_1=2\sigma_2$) on hardened steel EKh13 with 420°C, parts made of work-hardened steel of Kh18N10T, etc.

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Fig. 60. Decomposition cf stud pin made of steel of 25Kh2MFA after
12,000 h of operation with 480-500°C.

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Table 18. Test results for stress-rupture strength under conditions of stress relaxation.

Материал (1)	Температура, °С (2)	$\sigma_0, \text{МН/м}^2$ (кГ/мм ²) (3)	Среднее время между потяги- ями, ч (4)	Время до раз- рушения, ч (5)	Эквивалентное напряжение процесса $\sigma_a, \text{МН/м}^2$ (кГ/мм ²) (6)	
					по сумме относитель- ных долговечностей (7)	по предель- ной дефор- мации (8)
25Х2М1Ф (ЭИ723) [73]	580	500 (50)	24	371	375 (37,5)	385 (38,5)
			24	408	355 (35,5)	362 (36,2)
			24	416	338 (33,8)	347 (34,7)
			216	1080	278 (27,8)	292 (29,2)
			216	1305	273 (27,3)	288 (28,8)
		400 (40)	96	862	267 (26,7)	275 (27,5)
			96	969	288 (28,8)	293 (29,3)
			96	1054	271 (27,1)	278 (27,8)
			96	1092	289 (28,9)	294 (29,4)
			96	1156	260 (26)	268 (26,8)
20Х3МВФ (ЭИ415) [134]	550		96	1255	272 (27,2)	280 (28,0)
			96	1482	272 (27,2)	270 (27,0)
		1000		2368	227 (22,7)	239 (23,9)
			1000	2528	220 (22,0)	232 (23,2)
		350 (35)	1 (173)* 2 (13)* 4 (74)*	496	342 (34,2)	—
		350 (35)	1	707	337 (33,7)	
		400 (40)	1	96	376 (37,6)	
		450 (45)	0,1	12,5	417 (41,7)	
		450 (45)	1	41	398 (39,8)	
		450 (45)	10	120	352 (35,2)	
ХН80ТБЮА (ЭИ607А) [135]	650	450 (45)	100	1066	336 (33,6)	
		450 (45)	200	1145	336 (33,6)	
		200 (20)	11,5 (56)*	168	171 (17,1)	
			10 (7)*			
		200 (20)	24	1157	126 (12,6)	
	650	420 (42)	100	3149	346 (34,6)	
		450 (45)	1	337	425 (42,5)	
		450 (45)	10	750	370 (37)	
		450 (45)	100	2093	349 (34,9)	
		480 (48)	1	181	455 (45,5)	
		480 (48)	10	640	389 (38,9)	
		480 (48)	100	896	438 (43,8)	
		480 (48)	500	7103	278 (27,8)	

Note: In brackets is shown a number of cycles.

Key: (1). Material. (2). Temperature. (3). MN/m² (kg/mm²). (4). mean time between pull, h. (5). Time to failure, h. (6). Equivalent stress of process σ_3 , MN/m² (kg/mm²). (7). on sum of relative service life. (8). on maximum defcrmaton.

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With repeated loadings under conditions of relaxation, can be failed comparatively plastic materials.

The results of separate experiments regarding the service life of different steels and allicys under conditions of repeated relaxation are given in Table 18. As can be seen from Table 18, an increase in the time between pull increases the service life of material, but decreases a number of pulis, calling decomposition under conditions of relaxation.

The danger of decompsition under condititons of stress relaxation with repeated pull becomes real, especially pi the presence in the part of stress concentrators (deformations), sharply lowering the deformability cf material [139].

The intensification of the process of the depletion of the resource/lifetime of the plasticity of material during repeated relaxation can be observed also under conditions of creation with the tightening of the fastening of the plastic deformations during which, as it was shown above, is decreased resistance of relaxation.

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It is hence understandable, why one of the basic requirements, presented on the material of the fasteners of power units, which work under conditions of repeated tightening, is their high deformability.

The calculated methods of estimating the service life during relaxation with repeated pull are instituted on the determination of constant stress, called equivalent, that leads to destruction for the time, which corresponds to the conditions of work with the varying stresses: $\sigma_e = \sigma_{\text{all}}(\tau)$ or the calling for time testing the formation of strain of creep equal to creep strain, accumulated with varying stresses.

Calculations carry out on the basis of the following two hypotheses of stress-rupture strength with alternating loads: the hypotheses of the linear addition of damages and hypotheses of the linear addition of strains.

The hypothesis of the linear addition of damages consists under the assumption of equality to unity of the sum of the relative

damages:

$$\int_0^{\tau_p} \frac{d\tau}{\tau_{p_0}} = 1 \quad \text{or} \quad \sum_{i=1}^n \frac{\tau_i}{\tau_{p_i}} = 1, \quad (194)$$

where τ_i - operating time of material at stress σ_i and temperature T_i ;

τ_{p_0} and τ_{p_i} - time to failure when σ , T and σ_i, T_i respectively;

τ_p - time to failure at varying stresses and temperatures.

From determination it is evident that equations (194) can be utilized with the case of constant and variable of testing temperatures.

The hypothesis of the linear addition of damages was checked by a number of the authors with sporadically changing loads [111, 117-119, 140, 141], as a result of which was establish/install the possibility of its practical use during the calculation of the service life of materials at the temperatures, not calling change in the structure of material.

After accepting the constant velocity of creep during entire

testing (absence of local strain and third period), instead of expression (194) we will obtain

$$\int_0^{\varepsilon_p} \frac{d\varepsilon}{\varepsilon_{pg}(\sigma)} = 1, \quad (195)$$

where $\varepsilon_{pg}(\sigma)$ - strain during destruction under conditions of stress σ .

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The hypothesis of the linear addition of strains assumes that the destruction under conditions of varying stresses occurs when accumulated creep strain reaches limiting value for this time to failure without depending on the way of the accumulation of strain, namely:

$$\int_0^{\varepsilon_p} d\varepsilon = \varepsilon_p(\tau_p) \text{ or } \sum_{i=1}^n \frac{\Delta \varepsilon_i}{\varepsilon_{pi}(\tau_p)} = 1. \quad (196)$$

In connection with the fact that the deformability of material depends also on temperature, the use of criterion (196) is possible only at the condition of temperature constancy.

Under conditions when the deformation life of material does not depend on time, both of hypotheses give identical results.

Utilizing criteria (194) and (196) for the conditions of relaxation with periodic tightening, the curves of relaxation can be considered as curves of creep with gradually lowered by load. In these conditions in connection with the known law of a change of resisting the relaxation from cycle to cycle are calculated the values of the equivalent stresses in each cycle:

$$\sigma_e = \left[\frac{1}{\tau_p} \int_0^{\tau_p} \sigma^n(\tau) d\tau \right]^{1/n}. \quad (197)$$

$$\sigma_e = \left[\frac{1}{\tau_p} \sum_{i=1}^p \sigma_i^n \Delta \tau_i \right]^{1/n}, \quad (198)$$

$$\sigma_e = \frac{1}{m} \ln \frac{1}{\tau_p} \int_0^{\tau_p} e^{m\sigma(\tau)} d\tau \quad (199)$$

respectively on the basis of assumptions against exponential and exponential of the dependences of time to the failure:

$$\tau_p = A_1 \sigma^{-n}, \quad (200)$$

$$\tau_p = B_1 e^{-m\sigma}. \quad (201)$$

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The equivalent stress of entire process with respect can be found on the basis of values σ_e of each cycle (193). Thus, for instance, for the power law of the stress-rupture strength

$$\sigma_{s,cym} = \left[\frac{\tau}{\sum_{i=1}^k \frac{\tau_i}{\sigma_s^n}} \right]^{1/n}. \quad (202)$$

Furthermore, based on the hypothesis of the linear addition of strains and after considering that the creep rate with $\sigma=\text{const}$ does not depend on the time

$$\dot{\epsilon}_n = A\sigma^n, \quad (203)$$

$$\dot{\epsilon}_n = Be^{kn}, \quad (204)$$

we will obtain respectively

$$\sigma_s = \left[\frac{1}{\tau} \sum_{i=1}^p \sigma_i^n \tau_i \right]^{1/n}, \quad (205)$$

$$\sigma_s = \frac{1}{k\tau} \left[\ln \left\{ \sum_{i=1}^p e^{k\sigma_i \tau_i} \right\} \right]. \quad (206)$$

For power dependency $\dot{\epsilon}_n$ on σ

$$\sigma_{s,cym} = \left[\frac{1}{\tau} \sum_{i=1}^r \sigma_{si}^l \tau_i \right]^{1/l}. \quad (207)$$

Disregarding the unsteady stage of creep and utilizing formulas (52a) and (53a), let us substitute values τ and $d\tau$ into the equations, comprised on the basis of the hypothesis of the linear addition of the damages:

$$\int_0^\tau \frac{d\tau}{A_1 \sigma^{-n}} = \frac{\tau}{A_1 \sigma_s^{-n}}, \quad (208)$$

$$\int_0^\tau \frac{d\tau}{B_1 e^{-m\sigma}} = \frac{\tau}{B_1 e^{-m\sigma_s}}. \quad (209)$$

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We will hence obtain the following expressions for the equivalent stress of the cycle:

$$\sigma_s = \left[\frac{l-1}{n-l+1} \cdot \frac{\sigma_\tau^n \sigma_0^{l-1} - \sigma_0^n \sigma_\tau^{l-1}}{\sigma_0^{l-1} - \sigma_\tau^{l-1}} \right]^{1/n}, \quad (210)$$

$$\begin{aligned} \sigma_s &= \sigma_\tau + \frac{\sigma_0 - \sigma_\tau}{2} - \\ &- \frac{1}{m} \ln \left[\frac{k-m}{k} \cdot \frac{\operatorname{sh} \frac{k(\sigma_0 - \sigma_\tau)}{2}}{\operatorname{sh} \frac{(k-m)(\sigma_0 - \sigma_\tau)}{2}} \right]. \end{aligned} \quad (211)$$

The determination of equivalent stress according to the hypothesis of the linear addition of strains is based on expression for an average creep rate:

$$\dot{\varepsilon}_n = \frac{\varepsilon_n}{\tau} = \frac{\sigma_0 - \sigma_\tau}{E\tau}. \quad (212)$$

After accepting dependence $\dot{\varepsilon}_n$ on the stress in the form of expressions (203) and (204), we will obtain respectively

$$\frac{\sigma_0 - \sigma_\tau}{E\tau} = A\sigma_s^l, \quad (213)$$

$$\frac{\sigma_0 - \sigma_\tau}{E\tau} = Be^{k\sigma_s}. \quad (214)$$

After substituting for τ expression (52a) and (53a), let us find the which follow dependence equivalent stresses from σ_0 , σ_τ and the

slope/inclination of the curves of creep:

$$\sigma_s = \sigma_t \sqrt{\frac{(l-1)(\sigma_0/\sigma_t - 1)}{1 - (\sigma_t/\sigma_0)^{l-1}}}, \quad (215)$$

$$\sigma_s = \frac{1}{k} \ln \left\{ \frac{(\sigma_0 - \sigma_t)k}{e^{-k\sigma_t} - e^{-k\sigma_0}} \right\} \quad (216)$$

respectively.

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For dependence $\dot{\epsilon}_n = C \operatorname{sh}(m_1 \sigma)$ we have

$$\operatorname{sh}(m_1 \sigma_s) = \frac{(\sigma_0 - \sigma_t) m_1}{\lg \frac{\operatorname{th}(m_1 \sigma_0/2)}{\operatorname{th}(m_1 \sigma_t/2)}}. \quad (217)$$

At not too low a value $m_1 \sigma$ instead of expression (217) we will obtain

$$\sigma_s = \sigma_t + \frac{\sigma_0 - \sigma_t}{2} + \frac{1}{m_1} \left[\lg \{m_1(\sigma_0 - \sigma_t)\} - \lg \left\{ 2 \operatorname{sh} \frac{m_1(\sigma_0 - \sigma_t)}{2} \right\} \right]. \quad (218)$$

On the basis of the evaluation of the results of many calculations according to formulas (215) and (217) was proposed approximation formula [73]

$$\sigma_s = \sigma_t + 0.33 (\sigma_0 - \sigma_t). \quad (219)$$

In work [73] were compared the calculated equivalent stresses (see Table 18) with the stress-rupture strength of the material of the same melting, as testing for relaxation. Strain during destruction composed 1.6-3.1% that it attests to the fact that the region of nonuniform strain before destruction is comparatively small and the use the average creep rate does not introduce large error.

According to test results, were calculated the equivalent stresses of each relaxation cycle and entire process of up to the destruction (see Table 18) (Fig. 61).

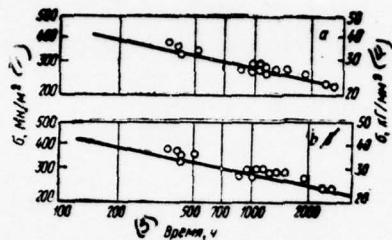


Fig. 61. Comparison of calculated equivalent stresses with the stress-rupture strength: a) the criterion of the sum of relative service life; b) the criterion of maximum strain; straight lines - stress-rupture strength; point - calculated equivalent stresses.

Key: (1). MN/m². (2). kg/mm². (3). Time, h.

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The comparison of the values of equivalent stress, calculated according to the hypothesis of the linear addition of strain (σ_{e_1}) and the hypothesis of the linear addition of damages (σ_{e_2}), shows (Fig. 61) that $\sigma_{e_2} > \sigma_{e_1}$, however, this difference is comparatively small. It should also be noted that the torque/moment of destruction in experiences of Ye. A. Heyn [73], L. P. Nikitina [134], L. Ya. Liebermann and N. I. Volkov [135] in many tests did not coincide with

the torque/moment of the application/appendix of maximum stress or the stress, corresponding to stress-rupture strength for this time. Elongation during destruction in all experiments proved to be the close to elongation during destruction under conditions of constant stress, corresponding to the same time.

Formulas of type (215) and (216) can be used also for determination σ_0 in cyclic relaxation tests - creep [135]. As an example Table 19 gives the results of such tests.

Table 19. Test results for cyclic creep - relaxation [132].

(1) Сталь	(2) Темпера- тура, °С	(3) Номер цикла	(4) Процесс	(5) τ, с	σ_3 МН/м ² (кг/мм ²) (6)	Повреж- дение τ_i/τ_{pl} (7)
ХН35ВТ (ЭИ612)	650	1	Ползучесть	853	225 (22,5)	0,405
		2	Релаксация	1500		0,0485
		3	>	864		0,054
		4	Ползучесть	70		0,179
		5	Релаксация	118		0,0121
		6	>	51		0,0086
			(10) Разрушение	3456	225 (22,5)	0,7082
		1	Релаксация	2217	284 (28,4)	0,0002
		2	>	1344		0,0005
20Х1М1Ф1 (ЭИ415)	550	3	>	502		0,0005
		4	Ползучесть	186		1,16
		5	Релаксация	1781		0,0052
		6	>	532		0,0026
		7	Ползучесть	130		0,0276
			(10) Разрушение	6692	284 (28,4)	1,196

Key: (1). Steel. (2). Temperature, °C. (3). Number of cycle. (4). Process. (5). h. (6). МН/м² (kg/mm²). (7). Damage. (8). Creep. (9). Relaxation. (10). Destruction.

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Table 19 shows that the use of a hypothesis of the linear addition of damages for estimating the service life under conditions of relaxation - creep is justified with a sufficient degree of accuracy ($\sum \frac{\tau_i}{\tau_{pl}} = 0,7 \div 1,2$). However, the analysis of values $\frac{\tau_i}{\tau_{pl}}$ shows

that the preferrel depletion of service life in these experiments occurred because of creep.

The hypothesis of the addition of damages we can be used also for estimating the service life of parts, that work under conditions of stress relaxation, which is accompanied by volumetric changes. Figure 62 gives the standard diagrams of a change in the stresses in the process of such tests. Curves of type I are characteristic for steel Kh12N20T3R with 600°C and initial stresses from 300 MN/m² (30 kg/mm²) and it is above [136]; under these conditions steel possesses very high creep strength, and the structural changes, calling volume change, they occur sufficiently intensely. Curves of type II are observed in materials, whose volumetric changes at initial stage are developed so intensely that suppress the processes of creep. In the course of time, structural changes attenuate and shape of the curve $\sigma=f(t)$ is determined by the processes of relaxation. This behavior was reveal/detected in steels Kh15N35VTu (EI787) with 600°C and initial stress 250 MN/m² (25 kg/mm²) and 4Kh12N8G8MFB with 500°C and initial stresses 200-360 MN/m² (20-36 kg/mm²). Are encountered in the practice of relaxation tests also curves of type III.



Fig. 62. Possible the curves of relaxation (I-III) during the decrease of the specific volume of metal depending on its deformability.

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Thus, for instance, this behavior under conditions of the rigid attachment of the length of specimen/sample was reveal/detected because of precipitation of the finely dispersed phase Ni₃Ti in steel Kh15N35VT with 600°C and $\sigma_1=250 \text{ MN/m}^2$ (25 kg/mm²).

In work [136] are described the cases of the decomposition of metals under conditions of relaxation with single loading under conditions of the developing structural changes.

Specimen/samples made of steel Kh12N20I3R, heat-treated under the standard conditions, which consists of tempering from 1170°C, 2

h, and aging at 750°C, 16 h, loaded to different initial stresses: 300, 400 and 450 MN/m² (30, 40 and 45 kg/mm²) and were tested at 600°C.

In the process of tests, steel was embrittled, as a result of which specimen/samples failed themselves for different time depending on value (Fig. 63).

To decomposition under conditions of the repeated cycles of stress relaxation, can be attributed decomposition with low-frequency low-cycle fatigue at the high temperatures under conditions of rigid loading (assigned/prescribed amplitude of strain) with the amplitudes of strain, which correspond to the stresses, the limit inferior of elasticity.

Under these conditions in each cycle, occurs stress relaxation, which decreases the value of calculated elastic stress, as a result of which cycle on the stress in such tests differs from sinusoidal.

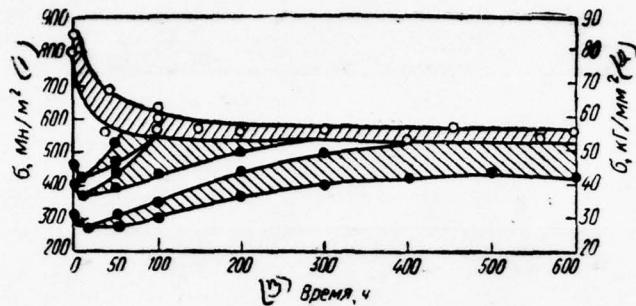


Fig. 63. Curves of relaxation of stresses and stress-rupture strength: of light small circles - stress-rupture strength; dark - unrelaxed stresses.

Key: (1). MPa/m^2 . (2). kg/mm^2 . (3). Time, h.

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However, this difference can be the essential only at the very high temperatures also of such periods of cycle during which the creep of the material leads to noticeable stress relaxation.

On the basis of the deformation treatments of the process of fatigue failure [119, 137] and of selection of the corresponding deformation criteria of decomposition under conditions of low-cycle

fatigue, the decomposition at the high temperatures under the conditions (in frequency and amplitude of strain) indicated is proved to be connected with the plastic deformation, accumulated because of stress relaxation during cycle.

Is proposed the following formulation of the criterion of decomposition under conditions of the low-frequency cyclic tests:

$$\sum_{i=1}^N (\Delta \varepsilon_{ni})^K = C, \quad (220)$$

where $\Delta \varepsilon_{ni}$ - range of a change in creep strain in cycle;

N - number of cycles before decomposition.

K and C - constant.

A change in value $\Delta \varepsilon_{ni}$ is determined by the character of the cyclic instability of alloy under conditions of creep at testing temperature.

For cyclically stable materials in tests from the assigned/prescribed by amplitude deformation, which changes according to rectangular law, value

$$\Delta \varepsilon_{ni} = \Delta \varepsilon_m = \varepsilon_0 - \frac{\sigma_r}{E} = \frac{\Delta \sigma}{E} \quad (221)$$

can be calculated by the theory of flow.

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In connection with tests with the short period of cycle, value
of $\Delta\sigma$ is low and strain $\Delta\varepsilon_m$ can be calculated when $\sigma(\tau) = \varepsilon_0(\tau)E$.

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Chapter VI.

EFFECT OF ALLOYING ON THE RELAXATION RESISTANCE OF ALLOYS.

In this chapter is examined the effect of the alloying cell/elements on the relaxation resistance of basic industrial alloys. Their number includes steels of pearlitic, ferrite-martensite and austenitic classes; alloys on ferrous nichrome and nickel-chromium bases; nonferrous metals their their alloys; refractory metals and alloys.

The best method of the development/detection of the character of the effect of the separate alloying cell/elements on the properties of the alloys of the studied system would be the establishment of the dependences between the content of this cell/element in alloy and relaxation resistance in the specific parameters (ϵ , t , r). The graphic representation cf such dependences is a special case of curves of composition-property, introduced into the procedure of the metallographic study by Acad. N. S. Kurnakov.

Unfortunately, the available experimental data insufficient in order to establish/install the dependences of relaxation resistance on the content of the alloying cell/element for the majority of industrial alloys. Thus far is only emitted the effect of the alloying of pearlitic, ferro-martensitic, and austenitic steels, and also partially alloys on basis Fe-Ni-Cr and Fe-Cr. Therefore the data, which concern enumerated steels and alloys, to more easily systematize and they are set forth more fully. In the ratio/relation to the alloys of nonferrous metals in the majority of the cases it is necessary to be satisfied with fragmented information which does not make it possible to obtain a full/total/complete picture of the dependence of their relaxation life on alloying.

One should note following.

The character of the effect of the alloying cell/element on the relaxation resistance of alloy can be different depending on initial heat treatment. The effect of the studied cell/elements is examined, as far as possible, after the optimum for alloys of this type of heat treatment, processing, which ensures highest relaxation life, taking into account other official characteristics.

2. Character of effect of alloying cell/element on relaxation resistance of alloy can be dissimilar at different temperatures. In

connection with this does arise the question, at what temperatures one should carry out the comparison of experimental data?

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Scarcely whether it would be expedient to study the effect of the alloying, for example, of pearlitic steel with 750-800°C, if it is known that this temperature knowingly exceeds the temperatures of relaxation softening and practical application/use of these steels. And, on the contrary, the dependences of the alloying of high-melting alloys, established/installation at 500-600°C, would not represent essential interest. From these considerations we examine the influence of alloying on relaxation resistance predominantly at the temperatures of the possible practical application/use of alloys of this type. Usually these temperatures are related to mean temperature region (0.25-0.50) T_{xx} (see Chapter IV, p. 4).

3. Character of influence of alloying cell/element in alloy can be various under conditions of short-term and prolonged stress relaxation. The available in the literature data are related to the most diverse intervals of time - from the portion/fractions of hour to several thousand hours. In essence we will be oriented toward the sufficiently prolonged periods, which ensure the onset of the steady relaxation time. In other all cases the duration of tests is

specified especially.

Subsequently will be examined only the basic laws governing the alloying of the alloys of different types in connection with their resistance of stress relaxation. The numerical characteristics of the relaxation resistance of typical steels and alloys are given only for the illustration of the set-forth laws governing alloying.

1. Steels of pearlitic class.

The relaxation resistance of steels of pearlitic class can be caused:

- 1) by strength and thermal stability of solid solution (ferrite), determined by its alloying;
- 2) by the chemical composition, by the type, by dispersity and thermal stability of carbide phases;
- 3) by interaction of secondary phases and solid solution, especially at elevated temperatures.

Different researchers give preference either to the first or to

the second, or third factors. In this case, in recent 10-15 years, was observed the specific evolution of views on this question. If earlier prevailing value they assigned to state and alloyed state of solid solution (ferrite), then recently the preceding role is abstract/removed to the strengthened/hardened phases.

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In our opinion, for the relaxation resistance of pearlitic steel can be heavy-duty/critical all three structure factors, moreover the latter of them, logically, is the consequence of first two. The relative value of each of these factors is determined by the ambient conditions, under which proceeds the process of the relaxation: by temperature, stress in by time. Hence it follows that to alloy relaxation stable steels of pearlitic class is expedient both by the cell/elements, which strengthen solid solution and by the cell/elements, which form excess (carbide) phases.

Before passing to the examination of the laws governing the influence of the alloying cell/elements on the relaxation resistance of pearlitic steel, it is necessary to stop at the role of carbon which most clearly is reveal/detected in plain carbon steel.

CARBON STEEL.

In connection with wide application in the machine-building of high steel (0.7-1.2% C) for the springs of different designation/purpose, that work at room and moderately elevated temperatures, and they also became with somewhat smaller carbon content (0.4-0.6%) for other parts, subjected to stress relaxation, a question concerning the optimum carbon content in such steels repeatedly were discussed in the literature. But in the overwhelming majority of works the attention of the researchers obtained only elastic properties (σ_y , σ_t) of steel with different carbon content. Thus, for instance, it is established, that with an increase in the content of this cell/element increases the effectiveness of strengthening steel because of martensite transformation with tempering, which makes it possible to obtain high elastic limit [142].

Data on the influence of carbon are directly on the characteristics of relaxation properties are extremely insufficient. Most thoroughly this question is studied by T. I. Volkova [70, 143]. Investigation underwent steel with the following carbon content: 0.025; 0.17; 0.4; 0.8 and 1.0% C.

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By relaxation tests (circular method) of unique duration (to 50000 h), with the initial stresses, equal to (0.7-0.8) σ_t , was establishinstalled gradual reduction of stresses for all mark/brands; however the intensity of process at room temperature is very small. So, after 50000 h the initial stress decreased in all by 1.5-30/o. In spite of extremely low absolute values of $\Delta\sigma$, it was possible to notice, that at 20°C the rate of the relaxation of stresses are less, the more in steel of carbon. In this case, steel from 0.4 and 0.8o/o C, that had the initial structure of the spheroidized pearlite, exerts larger resistance of relaxation, than the same steel with the structure cf lamellar pearlite. In steel with 0.17o/o C in both of structural components, relaxation resistance is virtually identical.

Steel with the same gradations of carbon content was tested for stress relaxation at temperatures 200, 300, 400 and 450°C for 3000 h [143]. If we change over obtained primary relaxation curves for meltings with different carbon content in the form of dependences of $\Delta\sigma - \sigma/\sigma C$, then such curves (Fig. 64) will have extreme character, moreover the position of maximum is different for different temperatures of testing.

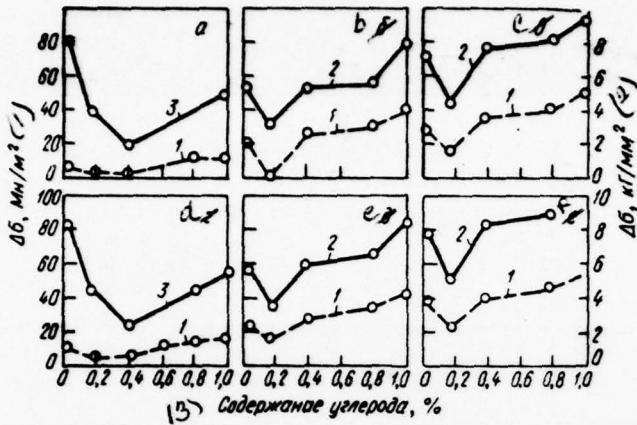


Fig. 64. The influence of the carbon content in steel on value of $\Delta\epsilon$ for the time of 1000 h (a-c) and of 3000 h (d-f) at temperatures 300 (a, d), 400 (b, e), 450°C (c, f) and $\sigma_0, \text{MN/m}^2 (\text{kg/mm}^2)$: 1 - 50(5); 2 - 100(10); 3 - 150(50) [143].

Key: (1) . MN/m². (2) . kg/mm². (3) . Content of carbon, o/o.

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Was hence made the conclusion/derivation that there is an optimum for each temperature carbon content, with which the relaxation resistance of steel is greatest. This is visually evident from the following

data:

(1) Температура, °C	200	250	300	350	400	440
(2) Оптимальный % C	0,6	0,5	0,4	0,3	0,2	0,15

Key: (1). Temperature. (2). Optimum.

Corrected values depend either on the level of initial stresses or from relaxation time (within limits from 200 to 3000 h).

Thus, with an increase in operating temperature the optimum for relaxation resistance carbon content in steel is gradually decreased. Similar pattern was establish/installled many years ago in the ratio/relation to creep strength [144].

The noticed law can be described by the proposed previously one of the authors [145] diagram of the influence of the carbon content in pearlitic steel on creep strength in dependence on temperature. It is obvious that this dependence can be common also for relaxation conditions. According to diagram (Fig. 65) it is allow/assumed the existence of temperature T_x , by which a change in the carbon content in steel does not affect resistance to creep and relaxation of stresses (is in form steady stage of both of processes). At less high temperatures (T_1-T_3) the carbon content favorably affecting the properties indicated, with higher (T_4-T_6) - it is negative.

This same diagram reflect/represents the fundamental dependence

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between the carbon content and mechanical properties (σ_y , σ_t , σ_b),
determined by short-term tests.

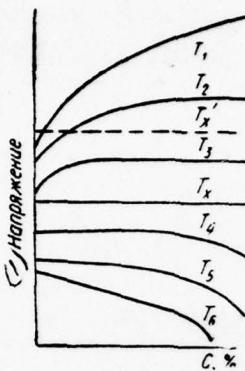


Fig. 65. Schematic dependence curves of the remaining stress from the carbon content in steel at different temperatures ($T_1 < T_x < T_6$)

Key: (1). Stress.

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However, the location of temperature T_x in Fig. 69 in this case will be misaligned into the region of higher temperatures.

Thus, it cannot be spoken about the optimum carbon content in steel irrespectively of operating temperature. In different temperature zones this influence can be different.

For steels of pearlitic class, alloyed by the carbide-forming cell/elements (chromium, molybdenum, vanadium), the proposed diagram of the influence of carbon on relaxation resistance somewhat is complicated, but in the majority of the cases, it remains in principle valid.

In the examination of the influence of carbon, it is necessary to consider the initial microstructure, created by heat treatment. Even in works [145, 146] it was shown, that the influence of carbon on creep of steel depends on the form of the cementite particles, which form pearlite. With the identical content in steel of carbon, resistance to small plastic deformations is above in steel with the structure of lamellar pearlite and it is less in steel with the structure of the spheroidized pearlite.

In light of modern representations this phenomenon can be explained by the fact that the plates of cementite are the larger obstruction for the displacement of dislocations, the cementite the globules. This does not contradict A. A. Bochvar's statement, which with globular structure is more than the areas of the possible emergence of plastic deformation, than with lamellar [147].

Is analogous the influence of the form of cementite particles under conditions of stress relaxation. At 300-370°C higher relaxation

life has steel with the structure of thin-plated pearlite whose coagulation to the same occur/flow/lasts more slowly than the rounded particles of cement¹.

FOOTNOTE 1. At the temperatures of the practical application/use of carbon steel as a relaxation-resistant material (300-350°C) with the spheroidizing of lamellar pearlite generally it is possible not to be considered. ENDFOOTNOTE.

However, at temperatures of <300°C, advantage of lamellar pearlite above the globular is considerably weaker, and at normal temperature, as was already noted above, under conditions of prolonged stress relaxation, is more preferable the structure of the spheroidized pearlite, ensuring higher elastic properties and relaxation resistance.

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LOW-ALLOY STEEL.

For the creation of relaxation resistance at elevated temperatures pearlitic steel they most frequently alloy by molybdenum, by chromium, vanadium; less frequent - by tungsten, by

titanium, niobium.

By V. Z. Tseytlin [148] was studied influence 0.20-0.64% Mo on the relaxation resistance of low-carbon steel (0.13-0.14% C) at different temperatures. Circular forms from experimental meltings with different content of molybdenum subjected to heat treatment - standardization with 900°C and to tempering with 650°C and experience/tested for relaxation with 450-550°C (Fig. 66).

It is possible to note that an increase in the content of molybdenum in low-carbon steel to 0.30% affects considerably more powerful the characteristics of relaxation resistance, than the subsequent increase in its concentration two times. Furthermore, molybdenum more intensely affects relaxation resistance during the first stage of the process when stress relaxation occur/flow/lasts with the decreased rate. The duration of initial section is decreased with an increase in molybdenum concentration, which one can see well from of the primary curves of Fig. 67. It is characteristic that at 500°C and in particular with 550°C an increase in the content of molybdenum smaller affects the value of the coefficient r_0 , than at 450°C (see Fig. 70). An increase in the temperature to 550°C leads low-carbon steel, alloyed only by one molybdenum, to essential relaxation softening.

In the majority of low-alloy steel, intended for fasteners, the average carbon content composes 0.2-0.3% C, which is connected with the need of achieving the higher elastic properties. In connection with this is of practical interest the influence of the alloying cell/elements on the relaxation properties of medium-carbon steel. In particular, in the work by T. I. Volkovoy and V. Z. Tseytlin [70] was studied the influence of chromium, molybdenum, vanadium and titanium. The chemical composition of the experimental meltings, the carbon content in which varied from 0.22 to 0.28% C, was given in Table 20.

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Figure 68 shows the influence of a change in the concentration each of the cell/elements indicated to relative value drop in voltage ($\Delta\epsilon/\epsilon_0 \cdot 100$) for 1000 h. It is possible to note that at 450°C all four cell/elements, conducted into steel separately, have noticeable effect on an increase in the relaxation resistance. At 500°C strengthened/hardened ability of these cell/elements under conditions of stress relaxation is considerably weaker, while with 550°C, by the exception/elimination of molybdenum, they little affect the relaxation resistance of steel (especially under conditions of prolonged service).

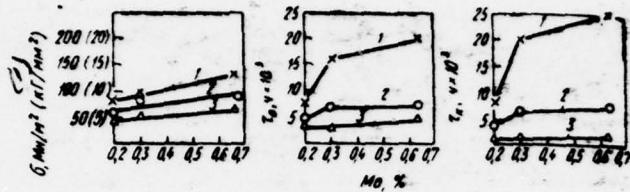


Fig. 66. Influence of the content of molybdenum in low-carbon steel on the characteristics of the relaxation: σ_0 , τ_0 and $\tau_k = \tau_0 \ln \sigma_0'$ at temperatures 450 (1), 500 (2) and 550°C (3) [148].

Key: (1). MN/m² (kg/mm²).

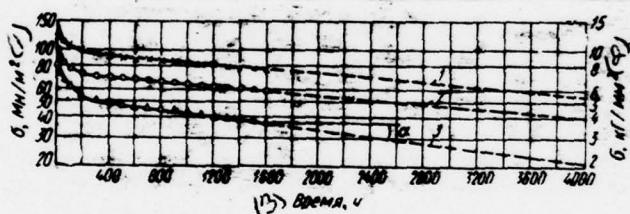


Fig. 67. Primary curves of relaxation of low-carbon steel with different content of molybdenum (at 500°C) : 1 - 0.64% Mo; 2 - 0.3%; 3 - 0.2% Mo.

Key: (1). MN/m². (2). kg/mm². (3). Time, h.

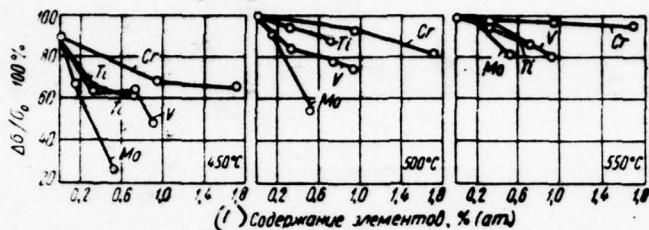


Fig. 68. Influence of content of alloying cell/elements in medium-carbon steel on value $\Delta\sigma/\sigma_0$ at different temperatures [70].

Key: (1). Content of cell/elements, % (at.).

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Most strongly increases relaxation resistance at all three temperatures molybdenum, then vanadium, titanium and less others - chromium. Addition to carbon steel 0.5% (at.) Mo is more effective than addition 0.9% (at.) V or 1.7% (at.) Cr.

Simple calculations show that 1% (at.) Mo increase the relaxation life with 550°C by 37.5%, vanadium - by 22%, titanium - by 16.5%. The strengthened/hardened action of tungsten is considerably weaker than molybdenum, and niobium - approximately the

same as vanadium.

In this connection it is appropriate to recall about the advantage of molybdenum before other alloying cell/elements in steels of pearlitic class also under conditions of creep [149 150]. This exceptional role of molybdenum is partly connected with the fact that in comparison with other cell/elements it most strongly increases the temperature of the recrystallization of ferrous alloys.

Table 20. The chemical composition and the hardness of low-alloy steel.

C	Si	Mn	Cr	(3) другие элементы	Твердость HB°
				(1) Содержание элементов, %	
0,27	0,60	0,73	—	—	131
0,28	0,28	0,44	0,9	—	150
0,22	0,22	0,54	1,8	—	159
0,27	0,60	0,73	—	—	131
0,30	0,30	0,67	—	0,24Mo	149
0,27	0,37	0,73	—	0,9Mo	228
0,27	0,60	0,73	—	—	131
0,24	0,30	0,64	—	0,30V	149
0,25	0,26	0,73	—	0,53V	—
0,26	0,21	0,65	—	0,84V	179
0,27	0,60	0,73	—	—	131
0,24	0,23	0,66	—	0,27Ti	140
0,23	0,36	0,76	—	0,60Ti	149

Key: (1). Content of cell/elements, o/o. (2). Hardness HB°.

FOOTNOTE 1. After standardization and tempering with 650°C.

ENDFOOTNOTE.

(3). other cell/elements.

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So, on data [15, p. 412], 0.60/o (at.) No increases the temperature

threshold of the recrystallization of iron from 500 to 600°C, but almost the second larger quantity of chromium [1.60/o (at.)] - only to 560°C. Furthermore, molybdenum, impeding diffusion processes, increases the stability of solid solution and carbide phase. Therefore completely important to keep the defined quantity of molybdenum in ferrite while the smaller part of the ferrite participates in the process of carbide-formation.

The positive influence of molybdenum distinctly is developed in the complex-alloyed pearlitic steel. By T. I. Volkova and V. Z. Tseytlin it is shown [to 70], that the introduction 0.25-1.00/o Mo to steel, which contains from 0.8 to 2.00/o Cr and to 0.40/o V (with 0.25-0.30/o C), increases its relaxation life with 450-550°C.

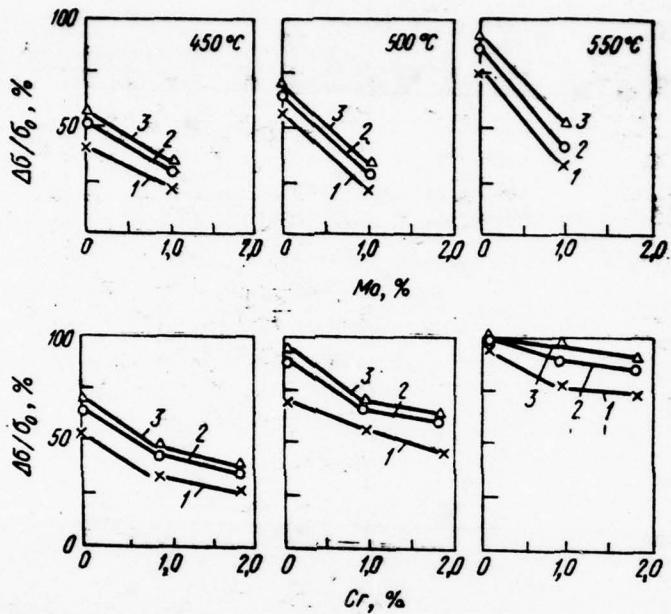


Fig. 69. Influence of the content of molybdenum in steel with 0.25% C, 2% Cr and 0.3-0.4% V and the content of chromium in steel with 0.25% C and 0.25% Mo on value $\Delta\sigma/\sigma_0$. Curves 1 - 100 h; 2 - 1000 h; 3 - 2000 h [70].

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Table 21. The chemical composition, o/o, and the fundamental characteristics of the mechanical properties of low-alloy steel for the fasteners of power units.

(1) Сталь	(2) Химический состав, %					(3) Рекомендуемая термическая обработка	(7) Температура, °C	(4) Кратковременная прочность			(5) Релаксационная стойкость	
	C	Cr	Mo	V	(6) другие элементы			$\sigma_{0,2}$	σ_b	$E \cdot 10^{-5}$	σ_{1000}	σ_{10000}
	(8) $MN/m^2 (kg/mm^2)$											
25Х1МФ (ЭИ10)	0,22 0,29	1,5 1,8	0,25 0,35	0,15 0,30	—	(7) Нормализация при 920° С + + отпуск 650° С 2 ч	20	800 (80)	900 (90)	2,17		
					—		500	590 (59)	630 (63)	1,80	120—160	80(8,0)*
							525	—	—		80—90	
25Х2М1Ф (ЭИ723)	0,22 0,30	2,1 2,5	0,9 1,1	0,3 0,6	—	(7) Нормализация при 1040° С + + нормализация при 960° С + + отпуск при 650— 680° С, 6 ч	20	830 (83)	960 (96)	2,17	—	—
					—		535	700 (70)	850 (85)	—	160(16)	100(10)
							550	570 (57)	650 (65)	1,70	140(14)	70(7,0)*
20ХМВБР (ЭИ144)	0,17 0,25	1,0 1,5	0,8 1,1	0,7 1,0	0,15Nb 0,05Ce 0,005B	(7) Нормализация 1040° С + + отпуск 600° С, 3 ч + + отпуск 720° С, 6 ч	20	800 (80)	950 (95)	2,20	—	—
							565	600 (60)	650 (65)	1,78	170 (17)	140 (14)*
							580	—	—		145 (14,5)	
20Х1М1Ф1ТР (ЭИ182)	0,17 0,24	0,9 1,5	0,8 1,1	0,7 1,0	0,15Ti 0,005B	(7) Закалка с 980° С в масле + + отпуск при 700° С, 6 ч	20	770 (77)	900 (90)	2,10	—	—
							565	580 (58)	600 (60)	—	165 (16,5)	130 (13)
							580	—	—	—	140 (14,0)	100 (10)

Note. $\sigma_0 = 300 \text{ MN/m}^2$ (30 kg/mm^2). Key: (1). Steel. (2). Chemical composition, o/o. (3). Recommended heat treatment. (4). Short-term strength. (5). Relaxation resistance. (6). other cell/elements. (7). Temperature, °C. (8). MN/m^2 (kg/mm^2). (9). Standardization with 920°C +relaxation 650°C 2 h. (10). Standardization with 1040°C +normalizatio with 960°C +relaxation at $650-680^\circ\text{C}$, 6 h. (11). Standardization 1040°C +relaxation at 600°C , 3 h + relaxation at 720°C , 6 h. (12). Tempering with 980°C in oil + relaxation at 700°C , 6 h.

FOOTNOTE 1. Extrapolated values. ENDFOOTNOTE.

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For an example Fig. 69 gives the graphs of a change in the relative stress of relaxation for steel with 0.25o/o C, 2o/o Cr and 0.3-0.4o/o V in dependence on the content of molybdenum. On the same diagram is shown a change in value of $\Delta\sigma:\sigma_0$ for steel with the constant content of molybdenum (0.25o/o) and the alternating/variable (from 0 to 1.7o/o) content of chromium. And in this case the influence of chromium is noticeably weaker than molybdenum.

By the experimental data, confirmed by practice, it is shown,

which for obtaining the maximum relaxation life at temperature of 500°C or above pearlitic steel is expedient to alloy simultaneously by two or three cell/elements. Especially effective proved to be compositions Cr-Mo, Cr-Mo-V, Cr-Mo-Nb, lying at the basis of most widely known fastening steels of pearlitic class whose brand chemical composition was given in Table 21. The properties of such steels are sufficiently fully described in the works by T. I. Volkova [74, 151], V. Z. Tseytlin [92, 148], Z. I. Petropavlovskaya [106]. Data on low-alloy steel, used for springs, that work at normal and elevated temperatures, are systematized in A. G. Rakhshadt's monograph [142].

MEDIUM-ALLOYED STEELS.

An increase in the concentration of the alloying cell/elements in steels of pearlitic class is higher than the limits, indicated in Table 21, it does not lead to further improvement in the relaxation resistance, and in a series of cases, even makes it worse. In accordance with this the content of molybdenum, tungsten, vanadium, niobium and titanium in real relaxation-resistant steels usually does not exceed 10%; the optimum content of chromium composes 1.5-2.5%.

For an increase scale and corrosion-resistance the content of chromium in pearlitic steel frequently is led to 30%, but sometimes

even to 5-6%. Such medium-alloyed steels (known are earlier by the name of semirefractory) on creep strength, they are inferior low-alloy, containing 1.5-2% Cr; however the information about their relaxation life in the literature was not until recently.

Given to Fig. 70a primary the curves of the relaxation of two complex-alloyed steels on basis 3 and 6% Cr to known degree complete this gap/spacing.

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An increase in the content of chromium from 3 to 60/o (with identical additional alloying) in the strongest degree accelerates the process of stress relaxation. The characteristics of relaxation resistance with 550°C in steel of Kh5MVFB are 2.5-3 times less than in the flock of Kh3MVFB (Table 22).

The data of Table 22 and of Fig. 70b give the representation of the effect of nickel on steel of the class in question. Introduction ~30/o Ni to steel of the type Kh3MFB sharply decreases resistance of relaxation of stresses (at 550°C). Let us recall that the nickel is not related to a number of cell/elements, which increase the creep strength of commercial iron and low-alloy steel, since this cell/element, introduced in small quantities, barely changes the activation energy in ferric alloys and it does not virtually increase the temperature of their recrystallization and softening.

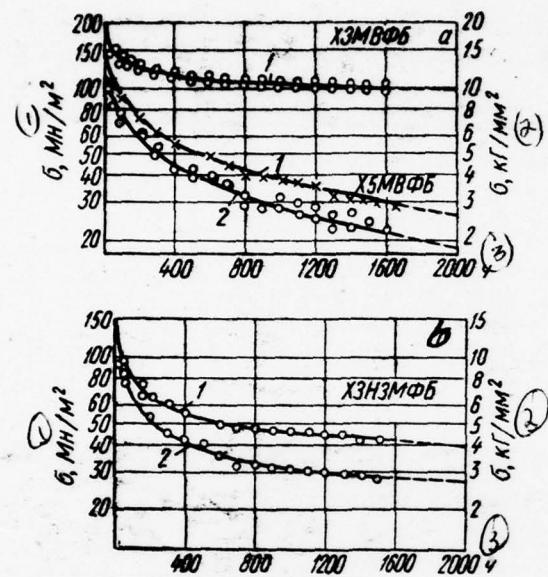


Fig. 70. Primary the curves of the relaxation of steels Kh3MVFB and Kh5MVFB (a) and Kh3NKhMFE (b) at 550°C and σ_0 , MN/m² (kg/mm²): 1 - 300(30); 2 - 250(25).

Key: (1) - MN/m². (2) - kg/mm². (3) - h.

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Table 22. Relaxation resistance of medium-alloyed steels.

(1) Сталь	(2) Примерный химический состав, %	(3) Темпе- ратура, °C	(4) σ_{∞} , МН/м ² (кг/мм ²)	(5) σ_t , МН/м ² (кг/мм ²), за время, ч			
				500	1000	1500	2000
X3MBФБ	0,17C; 2,9Cr; 0,4W; 0,4V; 0,5Mo; 0,6Nb	550	250(25) 300(30)	115(11,5) 117(11,7)	95(9,5) 108(10,8)	83(8,3) 100(10,0)	75(7,5) 96(9,6)
X5MBФБ	0,16C; 5,6Cr; 0,5W; 0,4V; 0,4Mo; 0,6Nb	550	250(25) 300(30)	40(4,0) 50(5,0)	30(3,0) 38(3,8)	23(2,3) 32(3,2)	18(1,8) 27(2,7)
X3H3BФБ	0,18C; 2,8Cr; 3,1Ni; 0,5Mo; 0,4V; 0,5Nb	550	250(25) 300(30)	40(4,0) 54(5,4)	32(3,2) 47(4,7)	29(2,9) 42(4,2)	27(2,7) 40(4,0)
X3K3MФБ	0,2C; 3,0Cr; 3,0Co; 0,6V; 0,6Mo; 0,4Nb	565	300(30) 350(35)	150(15,0) 166(16,6)	130(13,0) 147(14,7)	— —	114(11,4) 130(13,0)

Key: (1). Steel. (2). Exemplary/approximate of chemical composition, c/o. (3). Temperature, °C. (4). MN/m² (kg/mm²). (5). MN/m² (kg/mm²), for time, h.

FOOTNOTE 1. Extrapolated values. ENDFOOTNOTE.

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On data [144], the characteristic of creep of 3c/o nickel steel with 0.10-0.15% C with 400-500°C almost the same and plain carbon steel with the same carbon content (relationship/ratio of creep limits of nickel and carbon steel oscillates from 0.2 to 1.2).

Barely effective also proved to be introduction 2-3% Ni to chrome-molybdenum steel with ~10% Cr and 0.50/c Mo. Applied as early as the pre-war years in foreign turbine construction as fastening material chrome-nickel-molybdenum steel "Vitrac" (type of 30KhN3M) was subsequently replaced by chrome-molybdenum-vanadium and chrome-tungsten-vanadium steel [154].

However, so sharply negative an effect of nickel on the quantitative characteristics of relaxation resistance, what it render/showed into the steels of Kh3MFB (see Fig. 70b), until now, it was not reveal/detected. Apparently, it connected with presence in steel of vanadium and niobium, but to explain the reasons for this effect thus far is not possible.

Opposite influence exerts cobalt. During introduction to steel of the type Kh3MFB not less than 3% Co its relaxation life considerably grows/rises. Value σ_t for 2000 h of testing with 565°C and $\sigma_0=300 \text{ MN/m}^2$ (30 kg/mm²) in such a steel of Kh3K3MFB is 130 MN/m^2 (13 kg/mm²), but for steel of ~~Kh3MFE~~, this value with 550°C is 108

MN/m^2 (10.8 kg/mm²) (see Table 22). However, with the smaller content of cobalt (to 20%) of the positive effect of this cell/element on the characteristics of relaxation, it was not noted, what does not contradict the character of stress curve σ_t - % Co for 12% chrome steel, which relates to the martensite class (see Fig. 73).

2. Ferrite-martensite steels.

Are this involved chrome steel with 11-14% Cr, in dependence from the carbon content (0.1-0.30%), and of presence of the alloying cell/elements, these steels are related to martensite or (it is more frequent) to a ferrite-martensite class. Sc, with content of <0.15% C in the structure of flock with 11-13% Cr are about 10% of surplus ferrite. This quantity of ferrite can noticeably increase with additional alloying with such cell/elements as molybdenum, vanadium, tungsten, nickelium.

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The character of the structure of chrome steel, which contains 0.15-0.30% C, also depends on additional alloying. If carbon >0.30%, then 12% chrome steel with any of the virtually used combination of the enumerated cell/elements remains martensite.

The relaxation resistance of 12% chrome steel is determined by the numerical ratio of basic structural components (ferrite, martensite), by the degree of their alloying, by type and dispersity of carbide phases and structural stability under conditions of elevated temperatures.

The available experimental data on the study of stress relaxation in complex-alloyed chrome steel with 11-13% Cr confirm these positions and they make it possible to systematize the effect of the alloying cell/elements on the relaxation resistance of ferrite-martensite chrome steel.

First of all one should stop at the effect of carbon. From an experiment in the application/use of the stainless steel of brands 1Kh13, 2Kh13, 3Kh13, 4Kh13, it is known that with an increase in the carbon content with 0.1 to 0.4% are increased the yield points and elasticity of heat-treated steel at normal and moderately elevated temperatures (Table 23). However, to the relaxation resistance of chromic flock at elevated temperatures, carbon affects faster negatively. This fact was for the first time noticed by V. I. Smirnov [155], but it was not confirmed quantitative indices.

Table 24 gives the values of the remaining stresses after various relaxation time at temperatures 400 and 450°C for chrome

steel. the curves of the dependences of relaxation resistance with 450°C 12% chromic flock on carbon content are shown on Fig. 71.



Fig. 71. The effect of carbon on relaxation resistance 12% chrome steel with 450°C different duration, h: 1 - 100; 2 - 1000; 3 - 3000; 4 - 5000.

Key: (1) - MN/mm². (2) - kg/mm². (3) - Carbon content, %.

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Table 23. Mechanical properties of chrome steel [18].

(1) Сталь	Содержание (2) Углерода, %	(3) Термическая обработка	σ_T	σ_B	$\delta, \%$	$\psi, \%$	$a_{H^2}^{(5)} \partial Jc / m^2$ ($\kappa\Gamma \cdot \text{н}/\text{см}^2$)
			(4) $MN/m^2 (\kappa\Gamma/\text{мм}^2)$	$MN/m^2 (\kappa\Gamma/\text{мм}^2)$			
1X13	0,10—0,15	Отжиг при 860° C	200(20)	400(40)	23	70	100(10)
		Закалка 1050° C	800(80)	1000(100)	8	50	70(7)
		Отпуск при 500° C					
		Закалка с 1050° C,	550(55)	750(75)	12	55	80(8)
		Отпуск при 600° C					
		Закалка с 1050° C,	420(42)	600(60)	20	60	90(9)
2X13	0,16—0,24	Отжиг при 860° C	260(26)	500(50)	22	65	90(9)
		Закалка 1050° C,	950(95)	1250(125)	7	45	50(5)
		Отпуск при 500° C					
		Закалка с 1050° C,	650(65)	850(85)	10	55	70(7)
		Отпуск при 600° C					
		Закалка с 1050° C,	420(42)	600(60)	20	60	80(8)
3X13	0,25—0,34	Отжиг при 860° C	300(30)	550(55)	20	60	70(7)
		Закалка с 1050° C,	800(80)	950(95)	9	45	50(5)
		Отпуск при 600° C					
		Закалка с 1050° C,	500(50)	700(70)	15	55	50(5)
		Отпуск при 720° C					
		Отжиг при 860° C	350(35)	600(60)	20	60	70(7)
4X13	0,35—0,42	Закалка с 1050° C,	950(95)	1150(115)	13	47	20(2)
		Отпуск при 550° C					
		Закалка с 1050° C,	700(70)	900(90)	10	45	40(4)
		Отпуск при 700° C					

Key: (1). Steel. (2). Carbon content, o/o. (3). Heat treatment. (4).

MN/m² (kg/mm²). (5). J/m² (kg·m/cm²). (6). Annealing with. (7).FOOTNOTE¹. Cooling in air in all cases. ENDFOOTNOTE.Quenching. ¹(8). tempering with. (9). Quenching s.

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Table 24. Relaxation resistance 12c/o chrome steel.

Сталь (содержание углерода, %)	(2) $\sigma_0, \text{МН/м}^2$ ($\text{кг}/\text{мм}^2$)	(3) $\sigma_t, \text{МН/м}^2$ ($\text{кг}/\text{мм}^2$) за время, ч				
		100	1000	3000	5000	10000 ¹
<i>400° C</i>						
1X13 (0,10—0,15)	200(20)	166(16,6)	148(14,8)	141(14,1)	138(13,8)	121(12,1)
	250(25)	202(20,2)	163(16,3)	158(15,8)	153(15,3)	138(13,8)
	300(30)	231(23,1)	186(18,6)	183(18,3)	178(17,8)	160(16,0)
	200(20)	145(14,5)	137(13,7)	134(13,4)	130(13,0)	—
2X13 (0,16—0,24)	250(25)	181(18,1)	175(17,5)	166(16,6)	163(16,3)	—
	300(30)	227(22,7)	207(20,7)	180(18,0)	170(17,0)	—
<i>450° C</i>						
1X13 (0,10—0,15)	200(20)	133(13,3)	109(10,9)	98(9,8)	88(8,8)	72(7,2)
	250(25)	151(15,1)	124(12,4)	112(11,2)	107(10,7)	95(9,5)
	300(30)	173(17,3)	145(14,5)	128(12,8)	118(11,8)	101(10,1)
2X13 (0,16—0,24)	250(25)	122(12,2)	109(10,9)	90(9,0)	80(8,0)	—
	300(30)	156(15,6)	130(13,0)	108(10,8)	96(9,6)	—
	200(20)	113(11,3)	86(8,6)	73(7,3)	64(6,4)	—
3X13 (0,25—0,34)	250(25)	128(12,8)	95(9,5)	78(7,8)	68(6,8)	—
	300(30)	136(13,6)	113(11,3)	102(10,2)	94(9,4)	—
4X13 (0,35—0,42)	250(25)	129(12,9)	93(9,3)	—	—	—
	300(30)	150(15,0)	112(11,2)	—	—	—

Key: (1) - Steel (carbon content, o/o) - (2) - MN/m^2 (kg/mm^2) - (3) - MN/m^2 (kg/mm^2) for time, h.

FOOTNOTE¹. Extrapolated values. ENDFOOTNOTE.

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From these data it is evident that the presence of carbides in the structure of chrome steel is not decisive for its relaxation life, that is confirmed also in work [156]. Apparently, main role in strengthening of steel with 12% Cr play precipitation hardening and occurring during heating processes of redistributing of dislocations and emergence of segregations [157]. At the same time the particles of excess carbide phase must prevent movement of dislocation thereby exert the known strengthened/hardened influence. It is completely probable that the latter is developed with the smaller concentrations of carbon, for example from 0.01 to 0.1% (Fig. 71 these limits shows).

As can be seen from the data of Table 24, chrome steel of brands 1Kh13, 2Kh13 and 3Kh13 with 400-450°C possesses relaxation resistance, completely sufficient for its practical application/use as fastening material. However, at higher temperatures it sharply is softened. That, at 500°C in steel of 4Kh13 during 1000 h is retained 20% of initial stress, which was 200-300 MN/m² (20-30 kg/mm²). At 550°C in steels 1Kh13 and 2Kh13, the initial stress already during 500-1000 h relaxes with 250 to 10-15 MN/m² (from 25 to 1.5 kg/mm²).

The alloying of 12% chrome steel ~0.5% Mo little changes matter; in steel with 12% Cr, 0.5% Mo and 0.15% C at the same temperature and with initial stress value $\sigma_t = 10$ MN/m² (1 kg/mm²) is achieved for 2000-2500 h.

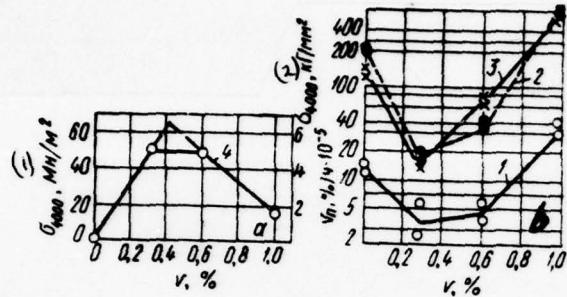


Fig. 72. The effect of vanadium on resistance of relaxation (a) and of creep (b) of steel with 12% Cr, 0.6% Mo and 0.15% C at different temperatures and with stresses, MN/mm^2 (kg/mm^2): 1 - 550°C, $\sigma=80$ (8); 2 - 600°C, $\sigma=60$ (6); 3 - 630°, $\sigma=40$ (4); 4 - 550°, $\sigma_0=25$ (2.5).

Key: (1). MN/mm^2 . (2). kg/mm^2 .

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Consequently, for creation by high relaxation resistance at 550-600°C is required the complex alloying of 12% chrome steel.

The results of the investigations, carried out in work [158, p 45], make it possible to establish/install some laws governing the effect of the alloying elements on the relaxation resistance of 12% chrome steel. It was established, that the alloying of steel with 12% Cr and 0.5% Mo with vanadium in quantity 0.3-0.5

leads to deceleration of the process of relaxation and, therefore, to an increase in value σ_r (Fig. 72) in connection with the fact that the presence of a small quantity of vanadium stabilizes basic martensite structure, since its significant part is expended/consumed on the formation of carbide VC. With the larger content of vanadium in the structure of steel, is observed a noticeable increase in the quantity of ferrite, in this case, is increased the concentration of the vanadium, dissolved in ferrite, as a result of which increases the rate of relaxation.

Let us note that vanadium has analogous effect on creep. And in this case is established/install [159] the optimum content of vanadium with which creep rate smallest (Fig. 72b); at 550°C it composes 0.3-0.6% (i.e. the same as under conditions of relaxation).

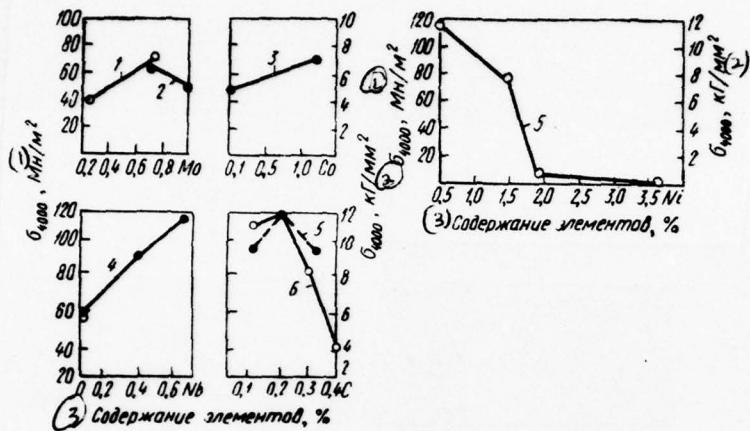


Fig. 73. Effect of the alloying of steel on basis 120/o CR on its relaxation life with 550°C $\sigma_0=250-300 \text{ MN/m}^2$ (25-30 kg/mm²), $\tau=4000 \text{ h}$. The chemical composition of steels, o/o: 1 - 1.0 W, 0.4 V, 0.15 C; 2 - 2 W, 0.4 V, 0.3 C; 3 - 1.0 Mo, 0.10 V, 0.10 C; 4 - 0.7 Mo, 0.4 V, 0.15 C; 5 - 0.7 Mo, 0.4 V, 0.7 Nb; 6 - 0.5 Mo, 0.7 W, 0.4 V, 0.6 Nb.

Key: (1). MN/m². (2). kg/mm². (3). content of cell/elements, o/o.

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With an increase in the temperature to 600-630°C, the minimum of creep rate in curves $v_n - \text{o/o V}$ is designated more clearly and answers 0.3o/o V.

Introduction 0.3-0.7c/o Mo to steel with 12o/o Cr, 0.4 V and

1-2% W leads to the even higher values of stress σ_r (Fig. 73). But an increase in the content of molybdenum in this steel to 1.0% causes decrease σ_r , which is connected with the total ferrite forming effect of molybdenum, vanadium and tungsten. In the structure of such a steel, are present the isolated sections of surplus ferrite. Alloying with tungsten was carried out in wider apparatus - from 0.5 to 4.0%. The results of relaxation test show that the introduction 1% W to steel with 12% Cr, 0.5% Mo and 0.4% V somewhat increases the resistivity of relaxation in comparison with steel without tungsten. However, further increase in the content of this element leads to a reduction in the value of the remaining stress (Fig. 74a). The fact is that during introduction to such a steel to 1-1.5% W its significant part remains in solid solution together with molybdenum, which leads to the retarding/deceleration/delay of diffusion processes and provides an increase in the relaxation resistance of steel. During an increase in the content of tungsten to 4%, latter goes not only for strengthening of martensite, but its essence for forming of considerable quantity of surplus ferrite resistance of relaxation of which is considerably below. Furthermore, the diffusion processes between ferrite and martensite reduce structural stability and thereby they contribute to a reduction in the resistivity of relaxation.

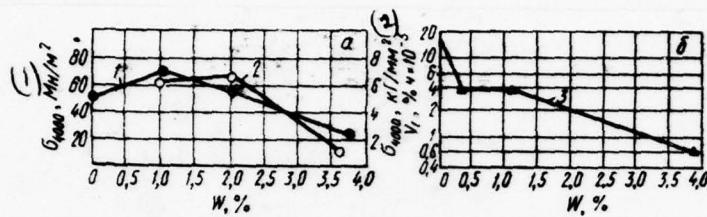


Fig. 74. the effect of tungsten on resistance of relaxation (a) and of creep (b) of 12% chrome steel with 550°C and σ_0 , MN/mm² (kg/mm²):
 1 - 0.6 Mo, 0.4 V, 0.15 C, $\sigma_0=250$ (25); 2 - 0.6 Mo, 0.4 V, 0.3 C,
 $\sigma_0=300$ (30); 3 - 0.7 Mo, 0.3 V, 0.10 C, $\sigma=80$ (8).

Key: (1). MN/mm². (2). kg/mm².

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At the same time it is known [for 159] that the presence 3-4% W in of 12% chromic flock leads to an increase in the resistivity of creep and stress-rupture strength (Fig. 74b). Comparative analysis of primary curves of relaxation and creep of steel with 12% Cr, 0.5% Mo and 4% W shows that the first stage of the process of relaxation in such a steel occur/follow/lasts with larger intensity than initial creep. Apparently, the process of a voltage drop is more sensitive to structural stability, than plastic strain with constant load (creep).

Very effective effect on the relaxation resistance of 12% chrome steel exerts niobium. So, the value of the remaining stress after 4000 h during introduction to 0.7% Nb to steel with 12% Cr, 0.5-0.7% Mo, 0.4% V and 0.15% C grows/rises approximately two times.

It is possible to assume that an increase in the resistivity of the relaxation of chrome steel with the alloying of it with niobium is caused by forming of stable particles of carbide of niobium NbC and by larger degree of the alloying of solid solution with molybdenum, vanadium, chromium, tungsten (because of impoverishment by these cell/elements of the basic carbide phase $M_{23}C_6$). In this case, the effectiveness of the action of niobium on an increase in resistance of the relaxation of high-chromium flock to a great degree depends on the content of other alloying cell/elements.

They proved to be invalid of attempt the relaxation resistance of chrome steel by nickel. Introduction to steel with 12% Cr, 0.7% Mo, 0.4% V and 0.7% Nb, nickel from 0.5 to 1 already leads to certain reduction in the resistivity of the relaxation (see Fig. 73). During further increase in the content of nickel in this steel, intensity of the process of relaxation sharply increases. In connection with this in chrome steel of a ferrite-martensite class, it is allowed/assumed by <0.2% Ni.

AD-A066 125 FOREIGN TECHNOLOGY DIV WRIGHT-PATTERSON AFB OHIO
RELAXATION OF STRESSES IN METALS AND ALLOYS. (U)

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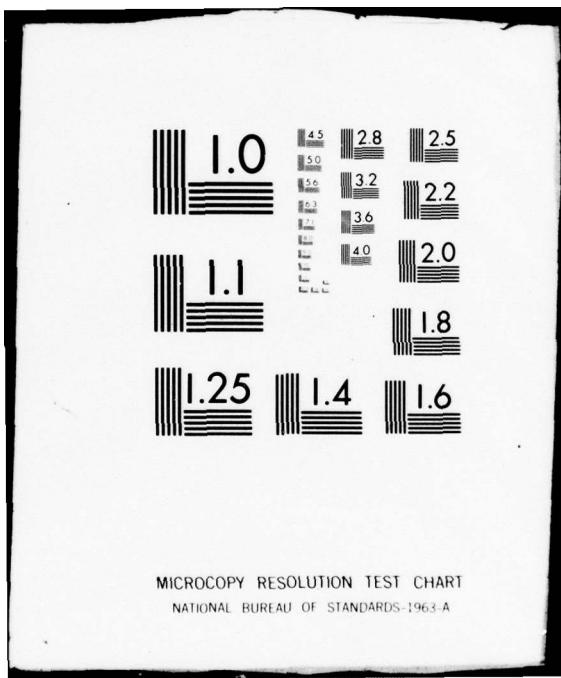
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Effect on the relaxation resistance of complex-alloyed chrome steel of a quantity of carbon in comparison with pure 12% chrome steel has some special features/peculiarities. With an increase in carbon from 0.1 to 0.2%, value σ_r insignificantly it grows/rises. Further increase in the carbon content sharply decreases value σ_r (Fig. 73).

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The decrease of relaxation resistance, apparently, is caused by forming in steel with 0.3-0.4% C after temper hardening of the structure of sorbite with the expressed orientation through martensite.

There is information about the modification of 12% chrome steel by the boron, introduced into steel in insignificant quantities (0.002-0.003%) for purpose of an increase in its heat-resistant properties. However, the data on the effect of small ones the addition of boron on relaxation resistance in the literature are absent.

In connection with this deserve attention the obtained in work

[158, p 34] data for steel of the type Kh10VMBF with addition 0.002% V and without it. Were obtained the following values of the remaining stresses after 10,000 h (after quenching with 1150°C and tempering with 650°C) (Table 25).

The positive effect of boron on relaxation resistance, at least, to 580°C does not leave doubts. It is known that boron contributes to the cleansing of the boundaries of the grains of metal and to the bonding of harmful low-melting impurity/admixtures in they are high-melting chemical compounds. The remaining part of the introduced into steel quantity of boron can directly increase resistance of steel of creep and relaxation. The addition of boron into steel Kh12VMBF is in practice utilized for an increase in its relaxation life (steel of the mark/brand of Kh12MBFR).

Thus, is established, that for an increase in the relaxation resistance of 12% chrome steel are most useful such cell/elements as vanadium, molybdenum and nickel, introduced separately or together.

Table 25. Effect of boron on the relaxation resistance of 10% chrome steel.

(1) Сталь	(2) Температура, °C	(3) $\sigma_{10000}, MN/m^2 (KJ/mm^2)$
(4)(без бора) X10ВМБФ	550	90(9,0)
	565	70(7,0)
	580	54(5,4)
	600	23(2,3)
(5)(с 0.002% B) X10ВМБФ	550	110(11)
	565	88(8,8)
	580	65(6,5)
	600	30(3,0)

Key: (1). Steel. (2). Temperature, °C. (3). MN/m^2 (kg/mm^2). (4). (without boron). (5). (with 0.002% B).

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Microalloying by boron [0.002-0.003% B (according to calculation)] even more greatly increases resistance of the relaxation of such steels.

Table 26 gives the fundamental characteristics of relaxation properties at operating temperatures of complex-alloyed chrome steel, which obtained industrial application/use. Their chemical composition is given in Table 27.

Enumerated steels on their relaxation life can be divided into two groups. In the first group enter steels of brands 1Kh12V1MF, 1Kh12V4MF and 1Kh11MFB for which the remaining stress after 1000 h at 550°C oscillates from 50 to 80 MN/m² (from 5 to 8 kg/mm²).

The second group includes steels of 1Kh12VVF and 2Kh12VMBFR with the higher values $\sigma_{1000}=110-140$ MN/mm² (11-14 kg/mm²) at 560-565°C.

In each group the best properties possess steels, which contain niobium.

Table 26. Relaxation resistance of modified 12% chrome steel.

(1) Сталь	Темпера- тура, °С	(3) σ_0 , МН/м² (кг/мм²)	$\sigma_t^{(4)}$ МН/м² (кг/мм²), за время, ч			
			500	1000	5000	10000
2Х13	550	250(25)	15(1,5)	10(1,0)	—	—
1Х11МФ	565	300(30)	50(5,0)	—	—	—
18Х11МФБ	550	300(30)	90(9,0)	80(8,0)	—	50(5,0)
1Х12ВНМФ (ЭИ802)	560	350(35)	130(13)	110(11)	90(9,0)	70(7,0)
	560*	350(35)	—	172(17,2)	136(13,6)	>120 (>12)
1Х12В2МФ (ЭИ756)	550	300(30)	80(8,0)	70(7,0)	60(6,0)	50(5,0)
1Х12В4МФ (ЭИ757)	550	300(30)	60(6,0)	50(5,0)	40(4,0)	30(3,0)
2Х12ВМБФР (ЭИ993)	565	300(30)	155(15,5)	140(14)	125(12,5)	106(10,6)
	565*	300(30)	200 (20)	182(18,2)	156(15,6)	133(13,3)

Key: (1). Steel. (2). Temperature, °C. (3). MN/m² (kg/mm²). (4). MN/m² (kg/mm²), for time, h.

FOOTNOTE 1. With twofold loading. ENDFOOTNOTE.

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A comparatively low relaxation life is characteristic for both of tungsten-bearing steels, in particular the mark/brand of 1Kh12V4MF, which is found in accordance with experimental data presented above through the effect of tungsten.

Highest relaxation life with 550-600°C from a number of those given in Table 26 possesses steel Kh12VMBFE. Value σ_t for 10000 h for it comprises: at 565°C 11 [(11), at 580°C 100(10) MN/m^2 (kg/mm^2) (after the optimum conditions/mode of heat treatment). As shown in work [22 p. 118], and also L. Ya. Liebermann [160, p 236], corrected values σ_t by the method of repeated loadings can be still raised - to 130 MN/m^2 (13 kg/mm^2).

Table 27. The chemical composition, o/o, modified chrome steel¹.

FOOTNOTE 1. The chemical composition according to GOST 5632-61.

ENDFOOTNOTE.

(1) Сталь	C	Si	Mn	Cr
2Х13(ЭЖ2)	0,16—0,24	≤0,6	≤0,6	12,0—14,0
1Х11МФ(15Х11МФ)	0,12—0,18	≤0,5	≤0,7	10,0—11,5
18Х11МФБ ²	0,10—0,17	≤0,5	0,5—1,0	10,0—11,5
1Х12ВНМФ(ЭИ802)	0,12—0,18	≤0,4	0,5—0,9	11,0—13,0
1Х12В2МФ(ЭИ756)	0,10—0,17	≤0,5	0,5—0,8	11,0—13,0
1Х12В4МФ(ЭИ757)	0,10—0,17	≤0,5	0,5—0,8	10,5—12,5
2Х12ВМБФР(ЭИ993)	0,15—0,22	≤0,5	≤0,5	11,0—13,0

(II) Сталь	W	Mo	V	Nb	Ni
2Х13(ЭЖ2)	—	—	—	—	≤0,06
1Х11МФ(15Х11МФ)	—	0,6—0,8	0,25—0,40	—	≤0,05
18Х11МФБ ²	—	0,6—0,9	0,3—0,4	0,25—0,35	0,6—0,9
1Х12ВНМФ(ЭИ802)	0,7—1,1	0,5—0,7	0,15—0,30	—	0,4—0,8
1Х12В2МФ(ЭИ756)	1,7—2,2	0,6—0,9	0,15—0,30	—	≤0,30
1Х12В4МФ(ЭИ757)	3,6—4,2	0,6—0,8	0,10—0,30	—	≤0,5
2Х12ВМБФР(ЭИ993)	0,4—0,7	0,4—0,6	0,15—0,30	0,2—0,4	≤0,35 ≤0,003B

Key: (1). Steel.

FOOTNOTE 2. The chemical composition by handbook on the metallic materials of turbo- and motor construction. Mashgiz [State Scientific and Technical Publishing House of Literature on Machinery Manufacture], 1961, p 517. ENDFOOTNOTE.

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3. Austenitic steels and Fe-Cr-Ni alloys.

If we examine resistance of the relaxation (with the constant of temperatures) of the series of the alloys of ternary system Fe-Cr-Ni with increasing content of one of the components, then this dependence can be expressed by curve "remaining stress σ_t - a quantity of alloying cell/element". Such curves with various initial stresses for one of the cut/sections (with 20% Cr) of diagram Fe-Cr-Ni are constructed in Fig. 75, moreover alternating/variable cell/element is the nickel whose content in this series of alloys was varied about 10 to 78% [93]. All alloys thermally machined to identical grain size.

It is obvious that curves σ_t - the content of nickel are characterized by typical for solid solutions slanting maximum.

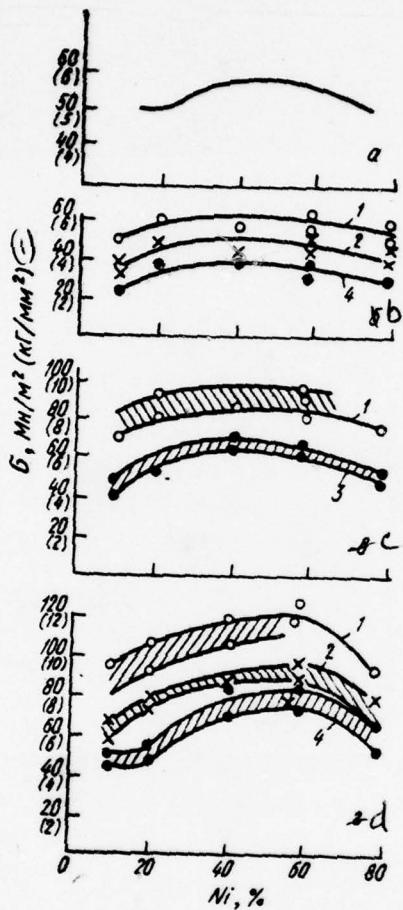


Fig. 75. Effect of nickel on creep limit for $v=10^{-6} \cdot h$ (a) and the remaining voltage of relaxation (b-d) in the alloys of ternary system Fe-Cr-Ni (cut/section with 100/o Cr) at 600°C. The duration of testing, h: 1 - 100; 2 - 500; 3 - 1000; 4 - 2000 s, MN/m^2 (kg/mm^2); b) 100 (10); c) 150 (15); d - 200 (20).

Key: (1) . MN/m^2 (kg/mm^2) .

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It is interesting to note that analogous form for the same cut/section of system Fe-Cr-Ni has curved limit of creep - content of nickel (Fig. 75a). The same character is established in the isotherms of hardness for the alloys of the cut/section indicated in the region of solid solution [161, 162].

Analogous with creep under conditions of stress relaxation at the relatively small intensity of process and duration to 10,000 h is noted the insignificant role of nickel in austenitic alloys with the constant content of chromium (with the condition of bringing the structure factors to by one denominator).

At the same time a change in the intensity of the process of relaxation can affect the character of curves the remaining stress - content of the alloying cell/element (see Fig. 75). With an increase in the initial stress σ_0 (and, consequently, the rate of relaxation) the effect of the alloying cell/element becomes more distinct. The decrease of initial stress, on the contrary, "levels out" the relaxation resistance of the alloys of different composition: curvature by curve σ_t - the content of nickel is smoothed.

The rate of the process of relaxation, which depends on value σ_0 , affects not only the curvature of curves and the value of maximum, but also its position along the axis of the chemical composition. From the same of Fig. 75, shows that with an increase in the initial stress the maximum on curves is shift/sheared along the axis of abscissas to the right, i.e., to the side of the larger content of the alloying cell/element (in this case from 40 to 55% Ni).

The effect of the content of nickel was studied also on some more compound alloys, relating to systems Fe-Cr-Ni-W, Fe-Cr-Ni-Mo and Fe-Cr-Ni-W-Mo with addition 1.5-20% Ti and without it. The content of chromium composed 15 and 20% [22, p 118].

In all cases the curves, which reflect a change of the characteristics of relaxation in dependence on the content of nickel (Fig. 76a), in multicomponent alloys retain the same character, as in ternary alloy Fe-Cr-Ni. However, in Fe-Cr-Ni-W-Ti and Fe-Cr-Ni-Mo-Ti alloys the maximum value of the remaining stress (for example, at 650°C) is observed with 25-27% Ni (on the analogous diagram of Fig. 75 this maximum when σ_0 answers ~40% Ni).

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Hence it follows that the position of the maximum of relaxation resistance in curves composition - property depends not only on the content of nickel, but also on the degree of the additional alloying of solid solution.

The discovered in the alloys of the studied systems maximums of relaxation resistance correspond to the maximum of the forces of the interatomic bond which with certain alloying depend first of all on the relationship/ratio of nickel and iron [15, p 412].

Figures 76 also shows that the molybdenum-containing austenitic alloys possess smaller relaxation life than being tungsten-bearing, which, apparently, is connected with the larger diffusion mobility of the atoms of molybdenum in γ -solid solution.

Figures 76.b shows the effect of tungsten on stress relaxation in Fe-Cr-Ni alloys of this type. In steel with 18% Ni, maximum relaxation life is observed already with 2.5% W; an increase in its content to 5% leads to noticeable reduction σ_t in alloys with 25% Ni there is the elongated maximum, which corresponds to 3-4% W, and finally in alloy with 35% Ni occurs a continuous increase in the relaxation resistance up to 5% W. Analogous laws gives the

effect of molybdenum.

Thus, for austenitic steels and alloys there is an optimum content of the alloying elements whose exceeding causes softening of solid solution.

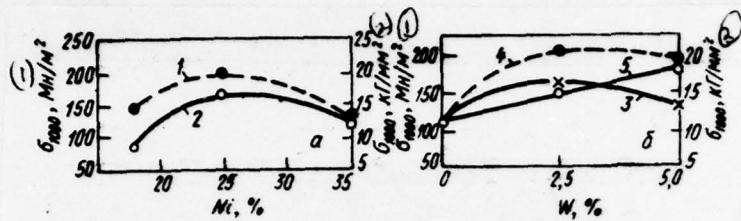


Fig. 76. The effect of the content of nickel (a) and of tungsten (b) in multicomponent alloy on relaxation resistance with 650°C , $\sigma_0=250$ kg/mm^2 (25 kg/mm^2): 1 - 2.5 W; 2 - 2.5 Mo; 3 - 15% Ni; 4 - 25% Ni; 5 - 35% Ni.

Key: (1) - kg/mm^2 . (2) - kg/mm^2 .

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This is explained, apparently, either by the impoverishment of the latter by some alloying elements in connection with an increase in the quantity of excess phases or forming of new type phases.

Excess phases in austenitic steels and alloys can be or intermetallic compound, since when, in carbon is present, fusion, - carbides of types MeC , Me_2C_6 , etc. In alloys with the sufficiently high content of nickel, the latter directly participates in the formation of the joints of types Ni_3Ti and $\text{Ni}_3(\text{Ti}, \text{Al})$, most frequently encountering in heat-resistant alloys. Together with them

are known also joints of the type Me'_2Me'' (Laves' phase) formable by iron with such cell-elements as tungsten (Fe_2W), molybdenum (Fe_2Mo), niobium (Fe_2Nb). The nature of the enumerated phases is examined in detail in works [19, 163].

Table 28 and 29 give given data on relaxation resistance of typical heat-resistant austenitic steels, reinforced because of carbide and intermetallide phases. Initial heat treatment consisted in quenching (austenitizing) under the optimum conditions and subsequent tempering (aging) for 6-24 h at the temperatures, exceeding on 50-100 deg testing temperature. From the comparison of Tables 28 and 29, show that they stopped with intermetallide strengthening they are characterized by larger relaxation life. the highest values of the remaining stresses has steel of Kh15N25V4T, and made of steels with carbide strengthening the best relaxation life in complex-alloyed steels cf 3Kh19N9 VTB and 1Kh14N18V2BR1.

Together with austenitic steels and alloys, which relate to system Fe-Cr-Ni, are known heat-resistant steels, which relate to systems Fe-Cr-Mn and Fe-Cr-Ni-Mn, that have satisfactory relaxation resistance [165, 195, p 22]. However, the systematic effect of the alloying cell-elements on stress relaxation in iron-chrome-manganese alloys was not studied with exception of work [166], in which was investigated the role of the carbide-forming cell-elements in steel

cf the type 2Kh12G12. The results of relaxation tests with 600°C and $\epsilon_0 = 120 \text{ MN/m}^2$ (12 kg/mm²) are represented in Fig. 77, from which it is evident that each of four cell/elements increases stress level σ_{2000} approximately to one and the same level 75-85 MN/m^2 (7.5-8.5 kgf/cm²).

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Table 28. Relaxation resistance of typical austenitic steels with carbide strengthening.

(1) Сталь	(2) Темпера- тура, °C	(3) $\sigma_{\text{ср}} \text{ Mn/m}^2$ (kg/mm ²)	(4) $\sigma_t, \text{ Mn/m}^2 (\text{kg/mm}^2)$, за время, h					
			100	200	500	1000	2000	5000
4X14H14B2M (ЭИ69)	550	200(20)	—	140(14)	—	—	—	—
	600	100(10)	—	51(5,1)	35(3,5)	25(2,5)	18(1,8)	—
	600	120(12)	—	70(7,0)	43(4,3)	29(2,9)	22(2,2)	—
X18H9T	600	100(10)	84(8,4)	82(8,2)	78(7,8)	72(7,2)	62(6,2)	—
	600	120(12)	98(9,8)	96(9,6)	90(9,0)	83(8,3)	72(7,2)	—
	600	150(15)	115(11,5)	110(11)	107(10,7)	98(9,8)	85(8,5)	—
	650	60(6)	44(4,4)	38(3,8)	34(3,4)	29(2,9)	21(2,1)	—
	650	100(10)	67(6,7)	61(6,1)	55(5,5)	50(5,0)	39(3,9)	—
	650	150(15)	98(9,8)	95(9,5)	89(8,9)	81(8,1)	65(6,5)	—
3X19H9MBТБ (ЭИ572)	560	200(20)	152(15,2)	—	147(14,7)	144(14,4)	139(13,9)	134(13,4)
	600	200(20)	138(13,8)	—	125(12,5)	117(11,7)	—	90(9,0)
	600	250(25)	160(16,0)	—	135(13,5)	123(12,3)	—	96(9,6)
	600	300(30)	180(18,0)	—	163(16,3)	139(13,9)	—	100(10)
	650	200(20)	110(11,0)	—	90(9,0)	82(8,2)	—	65(6,5)
	650	250(25)	130(13,0)	—	103(10,3)	91(9,1)	—	75(7,5)
4X18H25C2 (ЭЯ3С)	550	150(15)	—	123(12,3)	118(11,8)	113(11,3)	112(11,2)	—
	550	200(20)	—	155(15,5)	150(15,0)	147(14,7)	145(14,5)	—
	600	150(15)	—	124(12,4)	90(9,0)	81(8,1)	73(7,3)	—
	600	200(20)	—	100(10,0)	119(11,9)	117(11,7)	82(8,2)	—
1X14H18B2БР1 (ЭИ726)	650	150(15)	107(10,7)	—	99(9,9)	92(9,2)	88(8,8)	—
	650	200(20)	126(12,6)	—	118(11,8)	112(11,2)	105(10,5)	96(9,6)

Note. The chemical composition of steels according to GOST 5632-61.

Key: (1) - Steel. (2) - Temperature, °C. (3) - Mn/m^2 (kg/mm²). (4) - Mn/m^2 (kg/mm²), for time, h.

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Table 29. Relaxation resistance of austenitic alloys with intermetallic strengthening.

(1) Сталь	(2) Темпера- тура, °C	(3) σ_t , MN/m ² (kg/mm ²) ¹ , за время, ч				
		100	500	1000	5000	10 000
X15H18B3T (ЭП507)	650	—	188(18,8)	180(18,0)	160(16,0)	148(14,8)
X15H25B4T (ЭП164)		212(21,2)	204(20,4)	201(20,1)	178(17,8)	160(16,0)
X15H35BMT (ЭП692)		196(19,6)	185(18,5)	173(17,3)	152(15,2)	140(14,0)
X15H35BVT (ЭИ612)		210(21,0)	205(20,5)	199(19,9)	180(18,0)	160(16,0)
X15H35BKT (ЭИ612к)		210(21,0)	192(19,2)	180(18,0)	145(14,5)	120(12,0)
X15H25B4T (ЭП164)	680	204(20,4)	196(19,6)	185(18,5)	143(14,3)	120(12,0)
X15H35BMT (ЭИ692)		172(17,2)	150(15,0)	134(13,4)	108(10,8)	100(10,0)
X15H35BVT (ЭИ612)		168(16,8)	150(15,0)	126(12,6)	110(11,0)	100(10,0)
X15H35BKT (ЭИ612к)		190(19,0)	160(16,0)	145(14,5)	115(11,5)	90(9,0)

Key: (1). Steel. (2). Temperature, °C. (3) = MN/m² (kg/mm²)¹, for time, h.

FOOTNOTE 1. $\sigma_0=250$ MN/m² (25 kg/mm²). ENDPCCCTNOTE.

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However, if we judge the effectiveness of the specific cell/element

according to its minimum content in steel, which ensures obtaining the level of the remaining stresses indicated, then most effective are proved to be niobium and vanadium. It is sufficient a total of 0.5% (at.) of each of them for achievement $\sigma_{2000}=80 \text{ MN/m}^2$ (8 kg/mm²), and tungsten for this it is necessary to 1.25% (at.), molybdenum ~1% (at.).

It should be noted that for the stabilization of chrome-manganese-containing austenite which, as is known, is less stable, than chrome-nickel [167, 168], in all the experimental meltings, used for obtaining the dependences in Fig. 77, was introduced ~0.2% N. In the absence of the latter with the relatively high content of the elements indicated as a result of their ferrite-forming action, the structure of a series of meltings became two-phase ($\alpha+\gamma$) and the negative effect of ferrite component distorted the effect of the chemical composition.

In accordance with the data presented on the effect of alloying practical application/use under conditions of stress relaxation at elevated temperatures obtained chrome-manganese steel, additionally alloyed by vanadium, the exemplary/approximate composition: 0.2-0.3% C, to 1% Si, 12-15% Cr, 16-20% Mn, 0.5-0.8% V. Their relaxation life with 550-600°C is characterized by values σ_t , given in Table 30. As can be seen from these data, at 550°C

chrome-manganese-vanadium steel has very high relaxation life; during 2000 h it retains 75% from σ_0 .

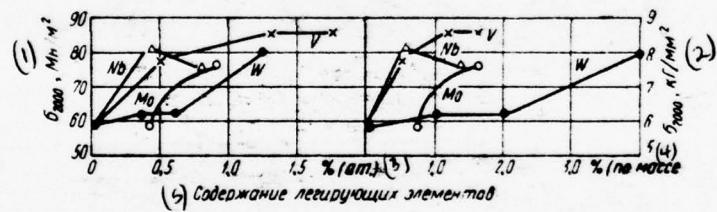


Fig. 77. Effect of the alloying cell/elements on the relaxation resistance of chrome-manganese steel of the type 2Kh12G12 at 600°C, $\sigma_0=120 \text{ MN/mm}^2$ (12 kg/mm²), $\tau=2000 \text{ h}$.

Key: (1). MN/mm^2 . (2). kg/mm^2 . (3). (at.). (4). (throughout mass).
 (5). Content alloying of cell/elements.

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Table 30. Relaxation resistance of chrome-containing and chrome-nickel-manganese austenitic steels.

(1) Марка и тип стали	(2) Темпера- тура, °C	(3) σ_0 , Mn/mm ² (kg/mm ²)	(4) σ_t , Mn/mm ² (kg/mm ²), за время, ч				(5) Исходная термическая обработка
			200	500	1000	2000	
3Х14Г20Ф (ЭИ729)	550 550	150(15) 200(20)	— —	— —	— —	110(11,0) 145(14,5)	(6) Закалка с 1150°C + + отпуск при 600°C, 5 ч
2Х15Г16Ф (ЭИ729А)	600 600	120(12) 150(15)	81(8,1) 98(9,8)	72(7,2) 90(9,0)	70(7,0) 82(8,2)	65(6,5) 77(7,7)	(6) Закалка с 1150°C + + отпуск при 700°C, 5 ч
3Х15Г16Ф	600	120(12)	90(9,0)	84(8,4)	76(7,6)	60(6,0)	(1) То же
2Х13Н4Г9 (ЭИ100)	600 600 600	100(10) 120(12) 150(15)	57(5,7) 66(6,6) 81(8,1)	47(4,7) 54(5,4) 66(6,6)	40(4,0) 47(4,7) 58(5,8)	33(3,3) 37(3,7) 45(4,5)	(6) Закалка с 1150°C + + отпуск при 700°C, 5 ч
4Х12Н8Г8МФБ (ЭИ1481)	600 600 600	100(10) 120(12) 180(18)	73(7,3) 96(9,6) 137(13,7)	70(7,0) 75(7,5) 124(12,4)	64(6,4) 69(6,9) —	59(5,9) 63(6,3) —	(6) Закалка с 1150°C + + отпуск при 710°C, 5 ч + 860°C, 5 ч

Key: (1). mark/brand and type of steel. (2). Temperature, °C. (3). Mn/mm² (kg/mm²). (4). Mn/mm² (kg/mm²), for time, h. (5). Initial heat treatment. (6). Quenching with 1150°C + tempering at. [4 = h]. (7). The same.

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At 600°C process of stress relaxation proceeds more intensely and in

the same period is retained a little more than 50% from σ_0 .

Chrome-nickel-manganese steels differ from chro-ma-containing ones in terms of more stable (but more heat-resistant) solid solution. And in the case Fe-Cr-Ni-Mn of basis high relaxation life is created by additional alloying, which is confirmed by the comparison of data for steels 2Kh13N4G9 and 4Kh12N8G8MFB. If at 2Kh13N4G9 for 2000 h with 600°C it was kept only by ~30% from σ_0 , then additionally alloy by molybdenum, vanadium and niobium steel of 4Kh12N8G8MFB under the same conditions retains >50% from σ_0 . It is characteristic that for reinforced by the enumerated cell/elements steels on Cr-Mn and Cr-Ni-Mn bases the level of the remaining stresses (at 600°C) is approximately identical (Table 30).

From the comparison of the data of Tables 30 and 28, it follows that chro-ma-containing and chrome-nickel-manganese austenitic steels on relaxation resistance in a series of cases are not inferior to chrome-nickel (with carbide strengthening). Thus, advanced even in the thirties position [144, 168, 169] that chro-ma-containing austenite on heat resistance is equivalent chrome-nickel, is confirmed under conditions of stress relaxation.

However, the possibilities of additional strengthening of chro-ma-containing austenite via alloying with tungsten, molybdenum,

vaniadium, niobium are strongly limited due to its insufficient stability as a result of which in steel easily are formed the two-phase structures $\gamma+\alpha$, $\gamma+\sigma$, which lead to a reduction in the relaxation resistance.

The practical application/use of chrome-containing and chrome-nickel-manganese steels as fastening material is limited to the which is inherent in them tendency toward embrittlement in the process of high-temperature service, and also to sensitivity to stress concentration.

4. Complex-alloyed alloys on basis Ni-Cr.

The study of the effect of the alloying cell/elements on the relaxation resistance of nickel-chromium alloys on the base of solid solutions was carried out by one of author together with V. Z. Tseytlin, by Yu. V. Latyshev and by G. G. Mcrozova [22, p 124].

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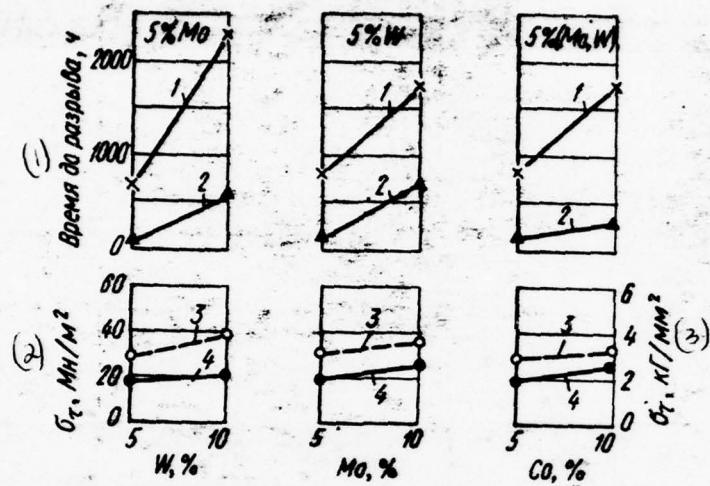


Fig. 78. Creep strength (time to rupture) at 700°C and relaxation resistance (σ_r) of alloys on basis Ni+15% Cr depending on the additional alloying: 1 - $\sigma = 150 \text{ MN/m}^2$ (15 kg/mm^2); 2 - 200(20); 3 - 6000 h with 650°C; 4 - 1500 h with 700°C.

Key: (1). Time to rupture, h. (2) - MN/m^2 . (3) - kg/mm^2 .

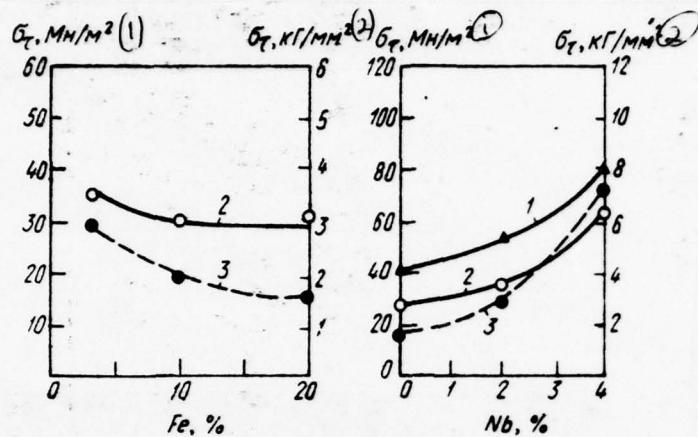


Fig. 79. The effect of riebium and iron on relaxation resistance (σ_r) of alloys Ni+15% Cr+5% W with $\sigma_0 = 150 \text{ MN/m}^2$ (15 kg/mm²): 1 - 2000 h with 650°C; 2 - 6000 h with 650°C; 3 - 1500 h with 700°C.

Key: (1). MN/m². (2). kg/mm².

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On of Fig. 78, are shown the effect of tungsten, molybdenum and cobalt. The introduction of these elements to 10% to Ni-Cr alloy with minimum (0.02-0.03) carbon content (with which it is retained the structure of uniform solid solution) exerts on relaxation resistance positive action, but not so/such considerable as to service life under conditions of creep.

The effect of niobium is more substantially (Fig. 79). However, one should consider that the single-phase structure of solid solution with alloying with niobium is retained approximately only to 30% Nb. Its larger content leads to the heterogenization of structure as a result of forming the intermetallide Ni_3Nb . The critical solubility of this phase in the binary alloy Ni-Cr composes 4.3% (at 700°C) [170]. In this case in connection with the additional alloying of alloy with tungsten and molybdenum the solubility in it of niobium, logically, is decreased and is within the limits by 3-4%.

Because of the need to establish/install the permissible content of iron in nickel-chromium alloys it was of interest to explain its effect on relaxation resistance. Figures 79 shows the negative effect of this cell/element on the relaxation properties of solid solutions on basis Ni-Cr.

The experimental data presented as a whole speak about the moderate relaxation life of the alloys, which have the structure of the uniform solid solution Ni-Cr, even with its additional alloying. Such alloys, apparently, it is necessary to alloy by the cell/elements, which do not only strengthen solid solution, but also forming excess phases, as this was shown on alloys with the niobium (see Fig. 79). The strengthened/hardened phases in alloys of this type is usually intermetallide joint, for example, of the type

$\text{Ni}_3(\text{Ti}, \text{Al})$, conditionally designated as a γ' - phase. The relationship/ratio in it of the atoms of titanium and aluminum depends on the relative content of these elements. In the case of the presence in the alloy of considerable quantities (>5-10%) of nickel or cobalt a γ' - phase can be described as $(\text{Ni}, \text{Fe}, \text{Co})_3(\text{Ti}, \text{Al})$.

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The analog of this intermetallique is the mentioned above connection Ni₃Nb. However, the latter scarcely whether can ensure the prolonged relaxation life of alloy, since it is metastable and afterward the more or less prolonged effects of temperatures of 700-800°C it transfer/converts into another modification with the rearrangement of crystal lattice from cubic that face-centered into rhombic, which leads to a reduction in heat resistance [171].

Connection Ni₃(Ti, Al) is more promising. Introduction to a nickel-chromium alloy of type 80-20 ~2.50/o Ti and 0.5-0.70/o Al, which leads to formation in its structure of γ'- phase (9-12o/o), considerably increases relaxation resistance with 600-650°C (Tables 31). However, since the solid solution of alloy is not reinforced by additional alloying, at higher temperature relaxation resistance considerably descends, in particular with high service lives (Fig. 80).

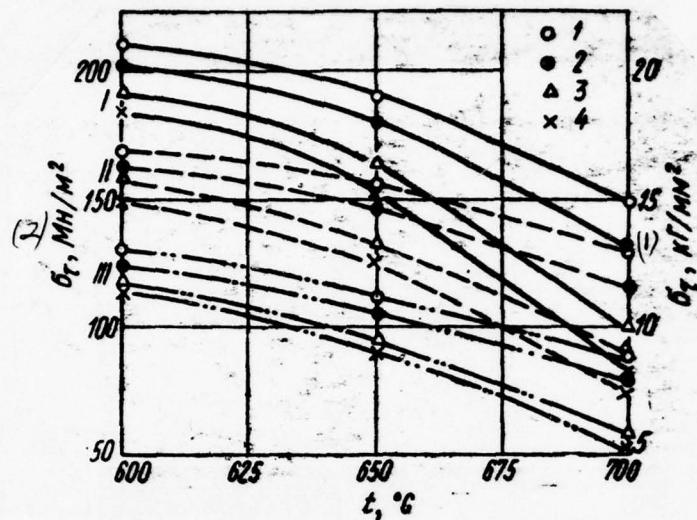


Fig. 80. Change in value σ_t in alloy Kn77Tyu in dependence on time and temperature of relaxation. The duration of testing, h: 1 - 500; 2 - 1000; 3 - 3000; 4 - 5000 σ_0 MN/mm^2 (kg/mm^2): I - 250(25); II - 200(20); III - 150(15).

Key: (1) kg/mm^2 . (2) MN/mm^2

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Table 31.

Comparison of the relaxation resistance of some nickel-chromium alloys¹ at 600-800°C.

FOOTNOTE¹. After tempering and stabilizing tempering. ENDFOOTNOTE.

(1) Сплав ^{**}	Темпера- тура, °C	⁽²⁾ $\sigma_{0.2}$, MN/m^2 (kg/mm^2)	⁽³⁾ σ_t , MN/m^2 (kg/mm^2), за время, ч / ⁽⁴⁾			
			1000	2000	5000	10 000 ^{*3}
X20H80	600	150(15)	52(5,2)	45(4,5)	—	34(3,4)
	600	200(20)	61(6,1)	55(5,5)	—	46(4,6)
XH77TIO (ЭИ437А)	600	200(20)	161(16,1)	158(15,8)	148(14,8)	128(12,8)
	650	200(20)	147(14,7)	138(13,8)	124(12,4)	103(10,3)
	700	200(20)	116(11,6)	101(10,1)	174(17,4)	46(4,6)
XH70BMTIO (ЭИ765)	650	0,5 $\sigma_{0.2}$	220(22,0)	200(20,0)	180(18,0)	170(17,0)
	700		175(17,5)	160(16,0)	140(14,0)	120(12,0)
	750		120(12,0)	106(10,6)	—	32(3,2)
	800		72(7,2)	—	—	—
XH65BMTIO (ЭИ893)	750	0,5 $\sigma_{0.2}$	173(17,3)	164(16,4)	146(14,6)	135(13,5)
	800	0,5 $\sigma_{0.2}$	120(12,0)	110(11,0)	70(7,0)	50(5,0)
XH67BMTIO (ЭП202)	800	0,5 $\sigma_{0.2}$	80(8,0)	—	—	—
	850	0,7 $\sigma_{0.2}$	92(9,2)	—	—	—
	850	0,7 $\sigma_{0.2}$	52(5,2)	—	—	—

^{*1} После закалки и стабилизирующего отпуска.^{*2} Химический состав см. ГОСТ 5632-61.^{*3} Экстраполированные значения.

Key: (1). Alloy 2.

NOTE 2. The chemical composition see Gost 5632-61. ENDFOOTNOTE.

(2). Temperature, °C.

(3). MN/m^2 (kg/mm^2). (4). MN/m^2 (kg/mm^2), for time, h. (5) ³.

NOTE 3. Extrapolated values.

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In this case, the effect of time factor is reinforced with an increase in the temperature, which is evident from the disagreement

of curves $\sigma-t$ in region of 650-700°C (Fig. 80). As a result with 700°C, after 3000-5000 h it is already retained only 30-40% of initial stress.

For an increase in the effectiveness of the strengthened/hardened action of excess phases and creation of prolonged relaxation life with 700-800°C, it is necessary, as already mentioned, to simultaneously alloy solid solution by tungsten, molybdenum, cobalt. In this case, the content of excess phases in alloy for providing for structural stability and prolonged plasticity must be within limits 20%. The isomorphism of their crystal lattice with the lattice of solid solution also contributes to the stability of heat-resistant properties.

Such principles of alloying answer, in particular, the alloys KhN67VMTYu, KhN70VMTYu, KhN70VMYU, KhN65VMTYu, relating to the six-component system Ni-Cr-W-Mo-Ti-Al. Let us pause on the last two in more detail, since their comparison makes it possible to explain the character of the additional effect of carbide phases. The alloys KhN70VMYU and KhN65VMTYu by the chemical composition are distinguished by the content of tungsten (5 and 10%) and of carbon, and also by the relationship/ratio of titanium and aluminum. In the first alloy ratio/relationship Al:Ti=1.5, in second one-to-one, total content of both of these elements virtually is equal (3-3.5%). The

higher carbon content in the alloy KhN70VMYuT (to 0.16%) causes formation together with the intermetallic phase Ni₃(Ti, Al) also of a noticeable quantity of carbide and carbonitride phases. In the alloy KhN65MTYu the basic strengthened/hardened phase is intermetallic Ni₃(Ti, Al); the content of carbonitride and boride phases is very small.

The advantage of the alloy KhN65VMYu on relaxation resistance with 750-800°C, in particular with prolonged service lives, is obvious from the data Table 31 [172]. The noted above special feature/peculiarities of phase chemical composition of both of alloys confirm that the "mixed" (carbide-intermetallic compound) strengthening of nickel-chromium alloys itself does not justify.

Table 32. Relative incidence/drop in the creep strength and relaxation resistance of heat-resistant alloys in the range of temperatures of 750-900°C.

(1) Сплав	(2) Темпера- тура, °C	(3) Относительное сопротивление ползучести	(4) Относительное напряжение релаксации
ХН70ВМЮТ (ЭИ765)	750	1	1
	800	0,65	0,51
	850	—	0,23
ХН67ВМЮ (ЭП202)	750	1	1
	800	0,68	0,61
	850	0,44	0,28
	900	0,24	—
ХН65ВМЮ (ЭИ893)	750	1	1
	800	0,65	0,65
	850	0,46	0,36
	900	0,26	—
ХН70ВМЮ (ЭИ617)	750	1	1
	800	0,73	0,66
	850	0,5*	0,33
	900	(0,30)*	0,10
ХН62ВМЮ (ЭИ867)	750	1	1
	800	0,74	0,50
	850	0,50	0,25
	900	0,32	—

* 3a 500 h. (5)

Key: (1). Alloy. (2). Temperature, °C. (3). Relative creep strength.
(4). Relative stress of relaxation. (5). After 500 h.

For the majority of alloys on nickel-chromium basis in interval of 800-850°C characteristically relaxation softening which occurs/flow/lasts more intensely than softening under conditions of creep. Even in the complex-alloyed alloys already after 100-120 h with 850°C it is retained 30-40% of the value of initial stress, and after 500 h - a total of 20-25% [173].

If we accept the values σ_u and σ_r at 750°C (after 1000 h) for 1, then relative stress-rupture strength with 850°C the mentioned heat-resistant nickel alloys it will comprise ~0.5; relative resistance of relaxation it oscillates within limits by 0.22-0.38 (Table 32). For 900°C we have with respect to 0.3-0.35 and ~0.10% (alloy EI617) [173].

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Thus, with an increase in the temperature "disproportion" between resistance of the alloy of creep and relaxation it increases (Fig. 81).

It should be noted that the which is inherent in nickel-chromium alloys relaxation softening in interval of 800-850°C cannot be avoided by heat treatment.

5. Nonferrous metals and their alloys.

The great variety of the procedures of test and evaluation criteria the relaxation resistances of nonferrous metals and their alloys extremely impedes the comparison of data on separate alloys. Therefore will be here noted only basic tendencies on the effect of alloying on relaxation stability of the separate groups of the alloys of nonferrous metals.

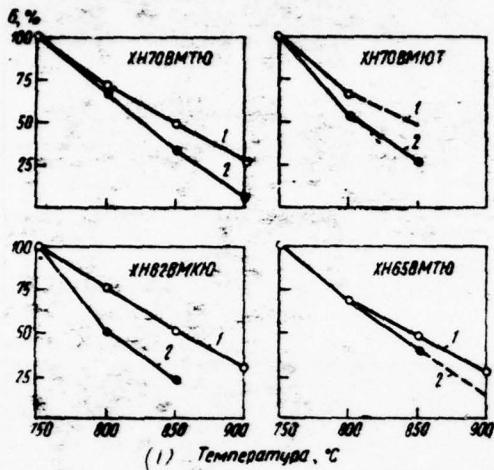


Fig. 81. A change in the creep strength and relaxation of typical nickel-chromium alloys in dependence on the temperature: 1 - σ_a after 1000 h; 2 - σ_t after 1000 h (σ_a and σ_t at 750°C they are accepted as 100%).

Key: (1). Temperature, °C.

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The distortions of crystal lattice of metal as a result of the dissolution of the atoms of the alloying cell-elements contribute to an increase in resistance of relaxation (and of creep). In some cases for this of sufficient hundredths and even thousandths added cell/element (microalloying), in others - several percentages more. Specifically, with strengthening because of the chemical distortion

of crystal lattice, is connected the known fact that some technical metals exert larger resistance of stress relaxation, than chemically pure. Thus, for instance, is matter with technical and pure aluminum, which contains 99.0 and 99.99% Al respectively. As another example of microalloying can serve the introduction of the micro-doses of bismuth to copper, which noticeably increases its resistivity of stress relaxation.

Further the low relaxation life of low-melting metal can be noticeably raised by macro-alloying. The intensity of relaxation of stresses (at room temperature) in tin during introduction to it 5% Bi or 5% Sb is decreased two times, during introduction to 3.5% Ag - to four, and 5% Cd - six times. Lead analogously affect magnesium, calcium and tin; zinc - aluminum and copper.

The relaxation resistance of commercial titanium in the range of temperatures of 20-500°C is substantially increased via its alloying with aluminum, chromium by molybdenum.

The effectiveness of the alloying of aluminum with copper, to copper by the nickel also of nickel by aluminum, chromium, cobalt and iron was shown in Chapter I (Fig. 5).

Light alloys. Stress relaxation in the alloys ATSM and AM on

aluminum basis is studied by D. I. Baykov [174]. The chemical composition and the value $\sigma_{0.2}$, MN/m² (kg/mm²): ATSM: 5.0% Zn, 1.8% Mg, $\sigma_{0.2} = 362$ (36.2); AM: 5.8% Mg, $\sigma_{0.2} = 187$ (18.7).

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Primary the curves of the relaxation of alloy AM with $\sigma_0 = 180$ MN/m² (18 kg/mm²) and temperatures from 140 to 200°C are given to Fig. 32. Characteristic is a sharp stress drop in the first hour of test at 180°C and in particular at 200°C. Subsequently the intensity of the process of relaxation is decreased.

Analogous form take primary curves, also, for the age-hardening alloy ATSM, for which the initial stress was two times higher (in accordance with higher yield point). Although the absolute values of the remaining stress for alloy ATSM are considerably higher, but if σ_t express in fractions of yield point $\sigma_{0.2}$, that the difference in kinetics of voltage drops in both of alloys will come to minimum.

Aluminum alloy with silicon (of type silumin) has that special feature/peculiarity, that relaxation of initial stress at temperature of -70°C occur/flow/lasts more intensely than at +20°C. This confirms the correctness of the temperature dependence of the relaxation, given to Fig. 39.

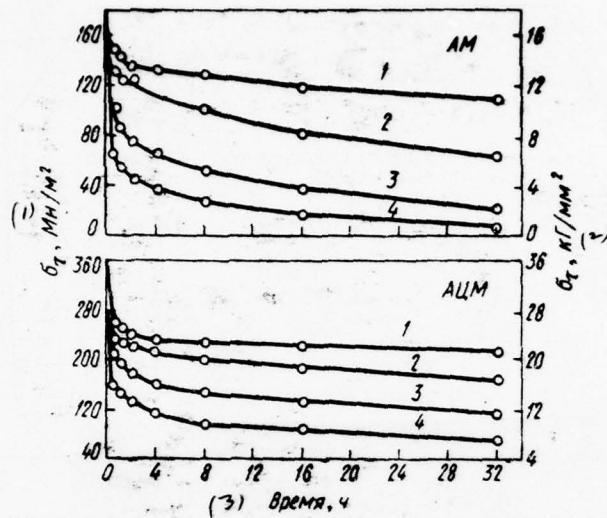


Fig. 82. Primary the curves of relaxation Al-Mg of alloys at different temperatures, °C [174]: 1 - 140; 2 - 160; 3 - 180; 4 - 200.

Key: (1) σ_1 MN/m². (2) σ_2 kg/mm². (3) Time, h.

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Jibbs and Hudson [175] published data on short-term stress relaxation in alloy on the magnesium basis Magnecx-AL-80 (0.80% Al, 0.004% Be) at temperatures from 100 to 450°C. Unfortunately, due to essential difference in the procedures of their tests it cannot be compared with the given above results for aluminum alloys.

Titanium and its alloy. The relaxation resistance of alloys on

the basis of titanium most systematic (over a wide range of stresses, time and temperatures) is studied in TskTI by L. P. Nikitina [9, 42]. By the author are constructed dependences $\Delta\sigma=f(\sigma_0/\sigma_{0,2})$. The examples of this dependence (proving to be rectilinear) for the alloy AT3 at temperatures 20 and 350-550°C are given to Fig. 83.

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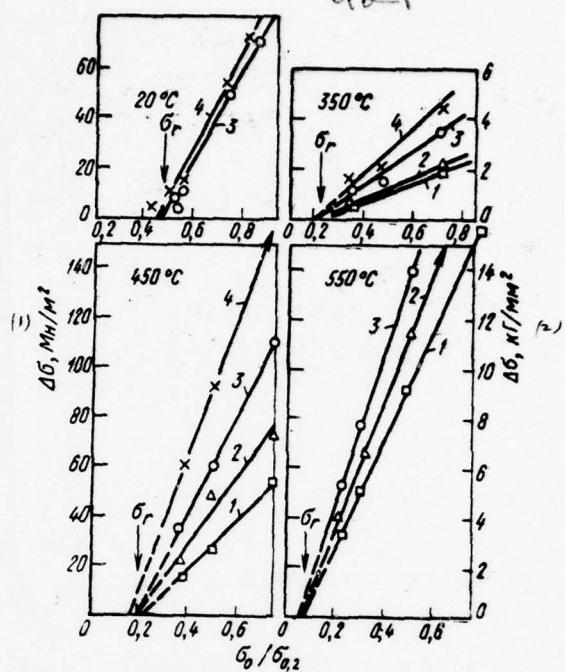


Fig. 83. The voltage drop is dependence on ratic/relation $\sigma_0/\sigma_{0,2}$ at different temperatures in titanium alloy A13 [42]. The relaxation time, h: 1 - 1; 2 - 10; 3 - 100; 4 - 1000.

Key: (1) MN/m^2 . (2) kg/mm^2 .

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It turned out that at 350°C value $\Delta\sigma$ for $\sigma_0/\sigma_{0,2} > 0.6$ is less than at 20°C. In other words, the intensity of the process of relaxation of stresses with 350°C is decreased in comparison with room temperature. This does not contradict the advanced concept about

the nonrectilinear character of dependence $\sigma_r - T$ in temperature range to 0.25 $T_{m\alpha}$ (see Chapter IV).

On Fig. 83, are determined the conditional (technical) limits of relaxation σ_r for the alloys, used in industry.

The led into Table 33 values σ_r give the representation of the effect of alloying on the relaxation resistance of titanium alloys, and also on the temperature of their relaxation softening. If at room temperature the limits of relaxation of both of alloys are identical, the same at 350°C for alloy VId value σ_r is two times higher than in alloy AT3. This testifies to the positive effect of molybdenum on the thermal stability of titanium alloys under conditions of stress relaxation and, besides to gas, once more confirms the inadequacy of characteristic value of the relaxation of alloys with 20°C for judgment about their relaxation life at elevated temperatures. Alloy AT3 as another titanium alloys with two-phase structure ($\alpha + \beta$), can be considered relaxation-resistant under conditions of prolonged service (by calculated hundred and by thousand of hours) to temperature of 400-450°C.

Table 33. Conditional limits of the relaxation of titanium alloys.

(1) Сплав	Температура, °C	(2) $\sigma_r, MN/m^2(kg/mm^2)$
AT3 (1.5%Al, 2.5%Cr)	20	375(37,5)
	350	90(9,0)
	450	80(8,0)
	550	20(2,0)
BT3 (6%Al, 3.5%Mo)	20	375(37,5)
	350	185(18,5)
	500	65(6,5)

Key: (1). Alloy. (2). Temperature, °C. (3). MN/m²(kg/mm²).

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In the work by G. I. Arkovenko et al. [176] was investigated the effect on the relaxation resistance of the alloys of VT3-1 and VT-14 of technological factors. In particular, it is shown, that the application/use of optimum conditions/modes of hot deformation, which increase the plasticity of titanium alloys, simultaneously increases resistance of stress relaxation, and vice versa. By endurance tests (to 1000 h) it is established, that an increase in operating temperature from 20 to 100°C virtually does not affect the relaxation resistance of alloy VT3-1, but in alloy VT-14, it somewhat is reduced.

Copper and copper alloy. Technical copper of the different

surface finish value served as the object of the study of its relaxation properties at room, the increased and reduced (lower than 0°C) temperatures. It is possible to note the investigations of B. M. Rcvinskiy [6], Feltem [98]. The constructed according to the experimental data of Boyd for oxygen-free copper of high purity/finish dependence $\sigma_t = f(\sigma_0)$ proved to be rectilinear at temperatures of 20-270°C, but already at 300°C ($\sim 0.4 T_{m1}$) straightness is disturbed [65].

The unique in duration tests (50 000 h) of technical copper (98% Cu) at the room temperature were carried out in TsNIITMASH by T. I. Volkovoy [70]. Initial stress composed from 0.25 to 0.42 $\sigma_{0.2}$. From curves $\sigma-\tau$ (Fig. 84) it is evident that stress relaxation in copper with 20°C occurs not only in the first, but also in the second relaxation time.

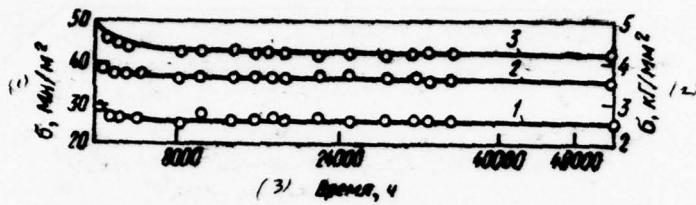


Fig. 84. Prolonged relaxation of stresses of commercially pure copper at room temperature [70] σ_0 , MN/m^2 (kg/mm^2): 1 - 30 (3); 2 - 40 (4); 3 - 50 (5).

Key: (1). MN/m^2 . (2) kg/mm^2 . (3). Time, h.

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However, the stress drop extremely little comprises for the values σ_0 a total of 5.5-8.5 of MN/m^2 ($0.55-0.85 kgf/mm^2$) accepted after 50 000 h.

From the basic groups of copper alloys, a great number of data on relaxation resistance is for beryllium bronze. This is explained by its relatively high elastic properties, which make it possible to use extensively a material indicated for manufacturing all possible springs, that work at room and moderately increased (to 150°C) temperatures.

Figures 85 gives data on the prolonged relaxation life (to 30,000 [REDACTED] h) of beryllium bronze of three standard mark/brands after different heat treatment (at room temperature) [142]. Best resistance of relaxation show bronze 1, Br.BNT and Br.E2.5.

FOOTNOTE 1. On GOST 493-54. ENDFOOTNOTE.

Considerably weaker is Br.E2, which in particular is noticeable with more prolonged service lives.

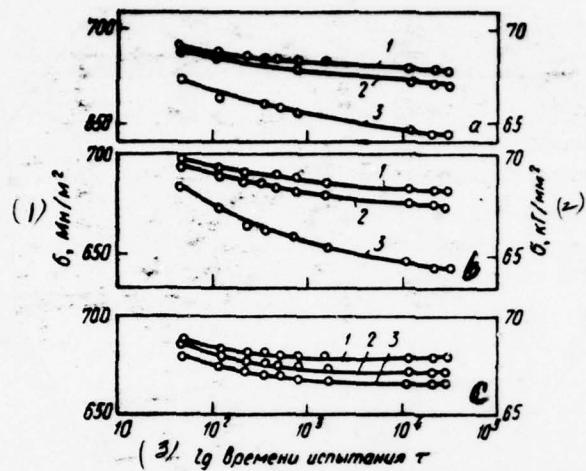


Fig. 85. Prolonged relaxation of stress with 20°C for beryllium bronze of the mark/brands Br.BNT (1), Br.B2.5 (2) and Br.B2 (3) after the heat treatment: a - tempering so on 300°C, 4 h; b - 320°C, 2 h; c - 350°C, 1 h [142].

Key: (1) . MN/m². (2) kg/mm². (3) . Time of testing τ.

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The relaxation resistance of aluminum bronze Br.A7 at the room temperature is lower than beryllium one and stannic phosphide [177, p 44]. With an increase in the temperature to 150-200°C, beryllium bronze retains its advantage, and stannic phosphide is somewhat inferior to aluminum on relaxation resistance.

Data on relaxation resistance (after 300 h) at the elevated temperatures of standard copper alloys, and also some alloys to the basis of nickel are given into Table 34 [142]. And here beryllium bronze, in particular brand Br.BNT-1.9, has obvious advantage at temperatures to 250°C above stannic phosphide and silicomanganese bronze. So, in bronze BNT-1.9 through 300 h with 200°C it is retained an additional 70% of initial stress. The stress-rupture strength of beryllium bronze with 200°C also is sufficiently high [178].

Table 34. Comparison of the relaxation resistance of some alloys on the basis of copper and nickel¹. (on data F. I. Mishkevich [142]).

Марка или тип сплава (1)	σ_t/σ_0 за 300 ч (% к начальному) при темпера- турсах, °C (2)					
	150	200	250	300	350	400
(3) Сплавы на основе меди						
Л-62	68	40	8	—	—	—
Бр.КМи3-1	82	50	25	—	—	—
Бр.ОФ6,5-1,5	82	50	25	—	—	—
Бр.Б2,5	88	65	25	—	—	—
Бр.БНТ-1,9	84	70	50	0	—	—
МНЦ15-20	96	90	70	52	35	15
6% (Ni+Co); 1,3% Al	94	85	75	60	42	23
(4) Сплавы на основе никеля						
ЭИ996 (2,3% Be)	—	97	96	94	90	80
2% Al, 5% Ti, 1% Nb	—	99	98,5	98	92	82
30% Co, 2,3% Ti, 1,75% Al	—	99	98,5	98	95	90
4,5% Re, 1% Al	—	99	98,5	98	97,5	80

Key: (1). Mark/brand or type of alloy. (2) after 300 h (o/o to initial) at temperatures, °C. (3). Alloys on basis of copper. (4). Alloys on basis of nickel.

NOTE¹. $\sigma_0 = 150 \text{ MN/mm}^2$ (15 kg/mm²).

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But for parts, that work under conditions of stress relaxation, maximum operating temperature of beryllium bronze is limited to 150°C [142].

At 300°C and above in beryllium bronze after the specific conditions/modes of heat treatment relaxation process can occur/flow/last anomalously (negative relaxation). In more detail this is examined in Chapter VII (see Fig. 108).

To a number of alloys on the basis of copper, can be attributed cupronickel alloys MNTs 15-20 and MNAu-1.5, ^{1.} are more known as German silver and Cunial.

FOOTNOTE 1. On GOST 492-52. END FOOTNOTE.

They possess the best relaxation life among copper alloys at the elevated temperatures (see Table 34), retaining, for example, at 250°C after 300 h 70-75% of initial stress.

The more detailed information about the mechanical and technological properties of copper alloys in connection with their heat treatment and designation/purpose is illuminated in A. G. Fakhshtadt's work [142].

Alloys on the basis of nickel in comparison with copper alloys have considerably high relaxation life with room and in particular at

elevated temperatures. Table 34 gives given data for two Soviet and two foreign alloys of this type, that find practical application/use for current-carrying springs [142].

Is most common nickelberyllium alloy EI966 (2-2.5% Be), that retains 90% of initial stress after 300 h with 350°C (see Table 34). Approximately identical resistance of stress relaxation has more complex in composition alloy with 5% Ni, 2% Al and 1% Nb (TAN-5-2-1). Optimum operating temperature of elastic cell/elements from the alloy EI996 of 250°C [142]. S. O. Tsotkalo et al. [177, p 97] give for the alloy indicated higher permissible temperature of 300°C. It should be noted that at this temperature the alloy possesses sufficient high 100-h stress-rupture strength 140 MN/m² (14 kgf/mm²).

Two last/latter alloys, mentioned in Table 34, differ little in relaxation resistance in the range of temperatures of 250-350°C; only at 400°C Ni-Co alloy has certain advantage. The latter, however, not is so/such substantial in order to justify the presence in alloy 30% Co or by 40% Re.

Besides the examined alloys, are widely known nickel fusions with 15-20% Cr (Nichrome). As relaxation-resistant material they in pure form are not applied, but they serve as basis for the creation

of the more complex-alloyed alloys with high resistance of relaxation and creep, examined in p. 4 present chapters.

Uranus the processes of stress relaxation in uranium investigated A. A. Tsvetayev, V. I. Bobenkc and Yu. N. Golovanov [179]. Tested uranium of the following chemical composition (o/o•10⁻³): 0.9 Fe; 1.6 Si; 1.0 Al; 2.0 Ni; 0.23 o/c Cu; 3.0 N; 60 C.

Via drawing metal was lengthened to the diameter of 1.3 mm and subjected to twofold phase recrystallization for removing the texture and to annealing for 6 h with 620°C.

Relaxation tests (with bend) carried out on the relaxation oscillator of stresses, in vacuum with 400, 450 and 500°C the stresses, not exceeding the yield point of uranium at this temperature (Fig. 86).

An increase in the intensity of stress relaxation for hardened/tempered and especially deformed uranium the authors explain by an increase in the degree of nonequilibrium of metal because of the presence in it of point defects.

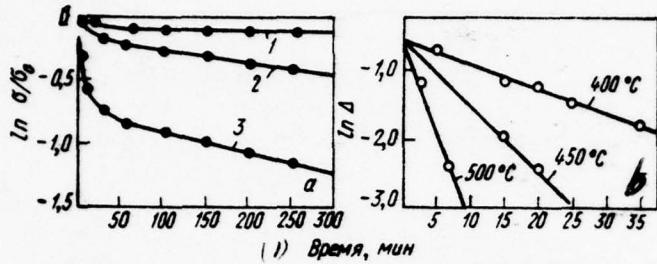


Fig. 86. Short-term stress relaxation in uranium [179]: a - primary the curves of relaxation with 200°C annealed (1), hardened/tempered (2) and deformed (3) uranium; b - dependence $\ln \Delta-\tau$ at different temperatures.

Key: (1). Time, min.

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Dependence $\ln \Delta-\tau$ for three temperatures (see Fig. 86) with the duration of experiments 40 min, has linear character. However, the authors note that in the presence of the stresses in metal, close to value $\sigma_{0.2}$, kinetics of the process of relaxation can be changed.

The schematic diagram of a change in the relative stress of relaxation in dependence on the temperature for the examined in present chapter basic alloys is given to Fig. 87. One should specify that the diagram is approximated, since the level of initial

stresses, satisfying condition $\sigma_0 < 0.8 \sigma_r$, it was not strictly identical, but the duration of tests varied within sufficiently wide limits (100-1000 h).

During the elongation of the relaxation time of point of inflection, that corresponds to the temperature of the beginning of relaxation softening, will be shifted to the left, i.e., to the side of smaller temperatures, and vice versa. More full/total/complete picture would give the series of similar diagrams for different relaxation time (for example, 10, 500, 1000 h and so forth).

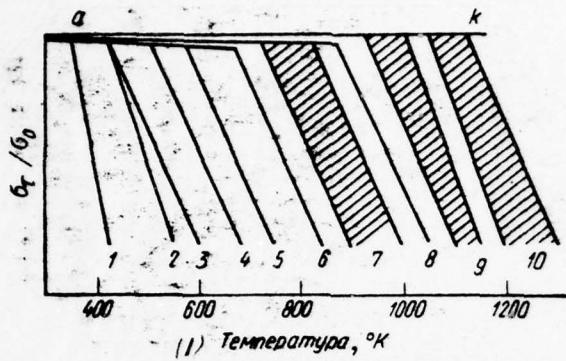


Fig. 87. The temperature effect on the softening of basic industrial alloys under conditions of relaxation (diagram): 1 - aluminum alloys; 2 - brasses; 3 - bronze; 4 - beryllium bronze; 5 - cupronickel alloys; 6 - titanium alloys; 7 - low-alloyed (pearlitic); 8 - 12% chrome steel; 9 - austenitic steels; 10 - nickel-chromium alloys.

Key: (1). Temperature, °K.

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However, the absence of experimental data thus far does not make it possible to construct such diagrams.

If we by Fig. 87 replace the scale of absolute temperatures by congruent ones, then the width of the interval between the extreme points a and k substantially will be reduced, i.e., curves will be drawn together. However, the full/total/complete coincidence of

curves for different alloys does not occur.

6. Refractory metals and alloys.

Metal testing for stress relaxation at temperatures is higher than 900-1000°C, of the corresponding to the technically advisable application/use refractory metals as relaxation-resistant material, are caused the essential methodological difficulties, which are even more aggravated by the low chemical stability of molybdenum, also, in particular niobium with 1000-1600°C. It is established, that in the process of endurance tests with 1300°C and above in vacuum occurs the saturation by oxygen of niobium, also, to a lesser degree of molybdenum, as a result of which the surface of the tested specimen/samples is oxidized [180].

Table 35. Properties of molybdenum alloy TsM2A.

① Температура, °C	② $\sigma_t, \text{МН}/\text{м}^2 (\text{кг}/\text{мм}^2)$		③ $E, \text{МН}/\text{м}^2 \cdot 10^{-5}$ ($\text{кг}/\text{мм}^2 \cdot 10^{-4}$)	④ $\sigma_0, \text{МН}/\text{м}^2$ ($\text{кг}/\text{мм}^2$)
	60	120		
20	660—720(66—72)		3,24*	—
900	380—430(38—43)		2,90	300(30)
1000	340—400(34—40)		2,85	310(31)

Continuation Table 35.

① Температура, °C	④ $\sigma_t, \text{МН}/\text{м}^2 (\text{кг}/\text{мм}^2), \text{за время, ч}$		
	60	120	500
20	—	—	—
900	177(17,7)	174(17,4)	167(16,7)
1000	171(17,1)	158(15,8)	135(13,5)

* При 100°C.

Key: (1). Temperature, °C. (2). MN/m^2 (kg/mm^2). (3). $\text{MN}/\text{m}^2 \cdot 10^{-5}$ ($\text{kg}/\text{mm}^2 \cdot 10^{-4}$). (4). MN/m^2 (kg/mm^2), for time, h.

FOOTNOTE¹. At 100°C. ENDFOOTNOTE.

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This partly explains scarcity, the literary these on high-temperature relaxation voltages in high-melting alloys. The available data are related to tests during several hours or even

minutes [181]. In connection with this are of interest the given in table 35 characteristics of the relaxation of molybdenum alloy TSM2A (0.20% Ti; 0.15c/c Zr) at 900-1000°C during the more prolonged periods of time. There corrected values of the yield point and module/modulus of elasticity E. These data testify to the sufficiently high prolonged relaxation life of alloy. So, after 500 h at 900°C it is retained 55%, and at 1000°C 45% of initial stress.

A. M. Borzdyka, N. N. Morgunov and V. A. Uzhik studied the anisotropy of the relaxation properties of sheet from alloy TSM2A with 900-1000°C and stresses $\sigma_0 \approx 0.8 \sigma_y$.

Annular specimen/samples cut from sheet in thickness 5 mm, moreover the axle/axis of the gash or the ring (see Fig. 21) in one case it coincided with direction of rolling, in other case it was perpendicular to the latter, and in the third it was inclined at an angle 45° to direction of rolling. Specimen/samples with the inserted in their gash wedges placed into the gasprccf muffle of horizontal electric furnace, which was filled with argon. Subsequently of testing, they carried out employing the common for annular specimen/samples procedure (see Chapter III).

Test result was not reveal/detected the clearly expressed anisotropy of relaxation properties. Experimental points for the

specimen/samples, manufactured by three methods indicated, on failure diagram or relaxation - time (Fig. 80) are packed in the outlined band which only is insignificantly wider than the common band of spread for annular specimen/samples.

The investigations of M. L. Bernstein [200] showed that the pre-created in molybdenum polygonal structure noticeably increases the resistivity of creep and stress relaxation.

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Testing the molybdenum, subjected to preliminarily thermomechanical treatment under different conditions, for stress relaxation was carried out at 900 and 1000°C and initial stress 240 MN/m² (24 kg/mm²). The best relaxation life showed the specimen/samples, deformed to 130% with 1150°C and then annealed for 40 h, which had the developed polygonal structure. Most sharply stress falls in the specimen/samples, deformed at 300 and 1150°C from the degree of reduction 50%.

From other refractory metals was studied short-term stress relaxation in niobium. On Zh. A. Sarzhent's data [181], at 1100°C initial stress in metallic rionium during 15 min relaxes with 200 of 50 MN/m² (from 20 to 5 kg/mm²), i.e., to 75%. Apparently, to

rely on the high-temperature application/use of niobium in pure form as relaxation-resistant material does not fall. To this is not eliminated the possibility of using the niobium as bases for heat-resistant and relaxation-resistant alloys.

D. A. Prokoshkin with colleagues [182] investigated the alloys of system Nb-Mo. The alloying of niobium with molybdenum as cell/element with higher melting point and with the larger strength of interatomic bonds leads to the decrease of the diffusion mobility of system even at so high a temperature as 1100°C ($\sim 0.5 T_{m1}$).

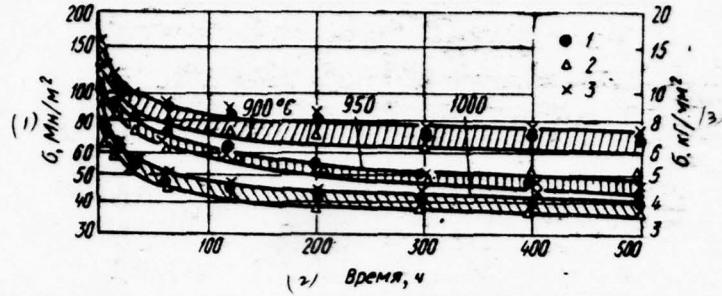


Fig. 88. The curves of the relaxation of the molybdenum alloy TsM2A, tested in vacuum at the different temperatures: 1 - axle/axis of the gash of ring coincides with direction of rolling; 2 - at angle of 45° to direction of rolling; 3 - is perpendicular to direction of rolling.

Key: (1). MN/m^2 . (2). Time, h. (3). kg/mm^2 .

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As a result with an increase in the content of molybdenum in alloy, the intensity of the processes of creep (and of stress relaxation) is decreased.

This is evident from Fig. 89, where is passed away a change in the logarithm of creep rate $\dot{\epsilon}$ at temperature of 1100°C and with different stresses in dependence on the content of molybdenum. Already 5-10% Mo give known effect, but an especially sharp

decrease in the velocity of creep is observed with 20% Mo. On the basis presented in Chapters I and II it is possible to assume that the effect of molybdenum will be analogous and in the ratio/relation to the rate of relaxation.

On the same of Fig. 89, shows the increase of energy, activation with an increase in the content of molybdenum.

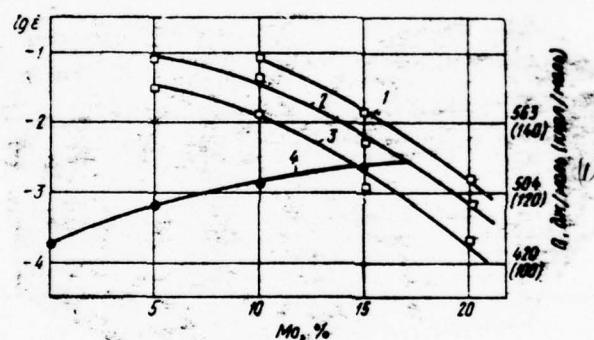


Fig. 89. Effect of the content of molybdenum in Nb-Mo alloy on creep rate with 1100°C (1-3) and energy of activation (4) [182]. The stresses of creep, MN/mm² (kg/mm²): 1 - 200 (20); 2 - 160 (16); 3 - 120 (12).

Key: (1). J/mole (kcal/mole).

Chapter VII

RELAXATION RESISTANCE OF ALLOYS IN CONNECTION WITH THEIR STRUCTURE
AND HEAT TREATMENT.

The relaxation resistance of alloys depends not only on the chemical composition, but also on their structure.

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It is possible to note common/general/total ones for all types of the alloys of special features/peculiarity, structural state which (directly or indirectly) affect the process of stress relaxation at common and elevated temperatures. Are this involved: the size of the grain of solid solution, its stability, quantity and sizes of the particles of the excess phases, their reciprocal location and interaction. The enumerated structure factors are regulated by heat treatment.

At the same time one should consider that the prolonged stay of alloy at elevated temperatures can substantially change the initial structural state, created by heat treatment.

1. Microstructure and relaxation resistance.

Positive effect on the relaxation resistance of alloys have all factors, which increase resistance to softening, retarding of return and which facilitate braking diffusion processes, and also created stable obstructions for movement of dislocation. As such obstructions can serve the phases of isclation/liberation in coherent state and in the form of highly dispersed particles, evenly distributed by volume grains of metal. The form of the fraction/particles of the phases of isclation/liberation must be such that their ccagulation at operating temperature would occur,flow/last more slowly. Therefore it is important so that their size/dimensions would be more identical, what to more easily achieve with the average particle sizes of the releasing phases. The arrangement of fraction/particles on the boundaries of the grains of solid scution impedes the mutual displacement of the latter and increases resistance of relaxation in initial period. The uniform arrangement of highly dispersed particles within grains of solid scution serves as the obstruction for movement of dislocation and for slip along the boundary/interfaces of subgrains, which increases relaxation resistance in the second period of process.

The effect of the basic parameters, which characterize the state of the phases of isclation/liberation (degree of dispersion, their

quantity, distribution in basement structure, etc.), on the process of creep sufficiently is well studied [18, 183], what cannot be said about stress relaxation.

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Z. N. Petropavlovskaya and S. A. Il'inykh [184] studied the influence of the degree of dispersion of the strengthened/hardened phases in ferrite and ferrite-martensite steel on basis 12-14% Cr on the course of the process of relaxation at temperatures of ~~not 1000-2000~~ 450-650°C ^Ah. For ferrite steel with intermetallic compound strengthening there is experimentally established the exponential dependence of the rate of relaxation in II period on average distance between the particles of an intermetallic (cf type AB₂) (Fig. 90a). However, in the case of carbide strengthening, this dependence has more complex character (Fig. 90b), which well agrees itself with Lin's calculated curve ~~pppy~~ (see Fig. 6b).

The structural stability of alloy in many respects determines its behavior under conditions of stress relaxation at high temperatures. The more stable the initial structure, the lesser the intensity of the process of relaxation of stresses (in the absence of additional factors). This was shown based on the example of complex-alloyed chrome steel of the type Kh12VMF [156]. An increase

in the temperature of tempering steel indicated from 650 to 700°C leads to the stabilization of basement structure, and in the process of relaxation of stresses (at 550-600°C, the additional isolation of carbides in steel after tempering with 700°C occurs less intensely, since in solid solution remains a smaller quantity of tungsten, chromium and molybdenum, than after tempering at less high temperature (for example, at 650°C).

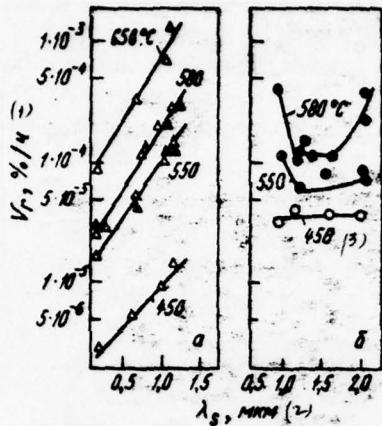


Fig. 90. Change in the rate of relaxation in dependence on average distance between the particles of secondary phase λ_s [184]: a) steel of the type OKh13VMF; b) steel of the type 1Kh13VMF.

Key: (1). o/o/h. (2). μm. (3). V.

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As a result of high-temperature tempering (at 700°C) imparts steel Kh12VMBF high relaxation resistance with 560-600°C, than tempering with 650-680°C (Fig. 91), despite the fact that the hardness and yield point (at 20°C and at 560-580°C) after more high-temperature tempering, logically, are below. The properties indicated are compared in Table 36.

Only an increase in the temperature of tempering to 720°C leads

to the relaxation softening of this steel (see Fig. 91).

The character of the decomposition of solid solution during heat treatment (tempering) also affects resistance of relaxation. The decomposition of solid solutions can be single-phase or two-phase. The continuous (single-phase) decomposition of solid solution, as a rule, it leads to higher relaxation rate. This confirm A. G. Rakhshstadt's data [142] for beryllium bronze in which the decomposition of the solid solution on two-phase type (with the formation of excess phases γ and γ'), realized by a tempering with 300-320°C, led to a sharp reduction in the relaxation resistance (see Fig. 85) in comparison with the specimen/samples, tempered at higher temperature (350°C), when decomposition was single-phase. Appearance in ferritic steel of the sections of austenite or, conversely, emergence in the austenitic structure of the areas of local $\gamma \rightarrow \alpha$ -transformation considerably makes relaxation resistance worse.

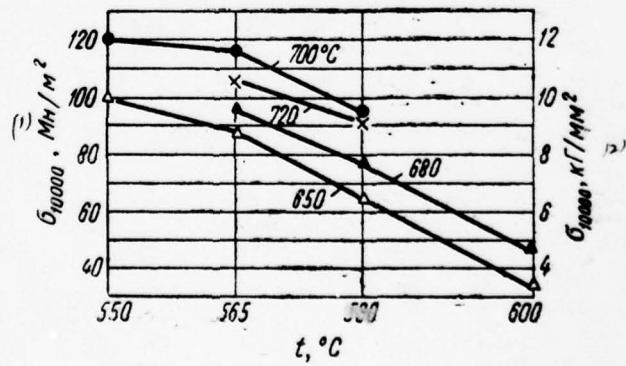


Fig. 91.

Fig. 91. The temperature effect of tempering on the value of the remaining stress in steel Kh12VMBF at $\sigma_0=300 \text{ MN/mm}^2$ (30 kg/mm^2).

Key: (1). MN/mm^2 . (2). kg/mm^2 .

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The more alpha-phase in the structure, the lower relaxation life. In exactly the same manner negative effect on the relaxation resistance of austenitic steels has the σ -phase, which is the intermetallic compound Fe-Cr.

The relaxation resistance of austenitic steels descends with the advent of α - or σ -phase first of all because the diffusion rate in these phases considerably (for ferrite on several orders) it is more than in austenite, in connection with which in them faster occurs/flow/last the phenomena of return.

B. A. Potekhin and I. N. Bogachev [99] showed, that the formation (at the temperature of liquid nitrogen) of martensite in the structure of austenitic chrome-manganese steel of the type 3Kh10G10 leads to intense stress relaxation.

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Thus, any damage of the structural uniformity of solid solution contributes to the development of the processes of relaxation.

Table 36. The temperature effect of tempering on mechanical properties and relaxation resistance of steel Kh12VMF.

Temperatura отпуска, °C	Твердость HB	σ_s	$\sigma_{0,2}$	σ_t^{∞}
		(3) MN/m ² (kgf/mm ²)		
650	302	950(95)	800(80)	—
	—	700(70)	670(67)	880(8,8)
	285	920(92)	780(78)	—
680	—	600(60)	570(57)	960(9,6)
	255	880(88)	680(68)	—
	—	560(56)	530(53)	1150(11,5)
700	241	820(82)	640(64)	—
	—	530(53)	500(50)	1070(10,7)
720	—			

Note. In numerator are shown the properties with 20°C, in denominator - at 560°C.

Key; (1). Temperature of tempering, °C. (2). Hardness. (3). MN/m² (kgf/mm²).

FOOTNOTE 1. After the quenching with 1050°C in cil.

2. σ_t for 10,000h with 565°C and $\sigma_{0,2} = 30$ MN/m² (kgf/mm²). ENDFOOTNOTE.

This is explained by the thermodynamic instability of the alloy in which were formed the local sectors of the structure, uncharacteristic of given external (temperature, pressure) and internal (chemical composition) conditions.

It is possible to expect decrease in the relaxation resistance of alloy, also, in such a case, when in basic solid solution are concentration heterogeneities. The latter can appear, for example, with the insufficient holding of steel during heat treatment. In some nickel-chromium and other alloys concentration heterogeneity is observed in connection with the emergence of so-called K-state [185].

The nonuniform distribution of the dissolved alloying elements in the lattice of base metal creates local microstrain (distortions), which are reflected in the stability of structural state and in the acceleration of relaxation processes (with sufficiently high temperature).

To a number of multicomponent alloys whose structure affects their resistance of relaxation sometimes to larger degree than the chemical composition, are related cast iron. Their relaxation life is determined, on one hand, by the metal base of structure (ferrite,

ferrite+pearlite, pearlite), and on the other hand - form and size/dimensions of graphitic particles.

Table 37. Results of relaxation tests of cast iron with 450°C [106].

(a) Условный номер плавки	(b) Вид чугуна	(c) σ_t / σ_0 (% к начальному) по истечени. ч		
		100	500	1000
1	Феррито - перлит- ный	35,0—40,0	26,0—31,2	22,4—26,5
2	Перлитный	40,0—47,5	31,5—39,5	28,0—34,0
3	Ферритный	31,8—40,0	23,2—30,0	20,4—26,0
4	Перлитный, леги- рованный 1,4% Mo+0,5% Cu	76,0—78,0	72,0—75,5	69,0—72,0
5	Перлитный, леги- рованный 0,5% Mo+0,5% Cu	75,0	70,5—71,5	66,5—69,5
6	Литая сталь 25Л	49,0—50,0	42,0—42,5	38,8—40,0

Key: (a). Conditional number of melting. (b). Form of cast iron. (c). to initial) after, h. (1). Ferrite - pearlitic. (2). Pearlitic. (3). Ferrite. (4). Pearlitic, alloyed. (5). Pearlitic, alloyed. (6). Cast steel 25L.

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The greatest relaxation life (at temperatures to 450-500°C) possesses, as a rule, cast iron with pearlitic basis, small-cast iron with ferrite basis (Table 37). Ferrite-pearlite cast iron occupies intermediate place.

As concerns graphitic component, then in the number of investigations is noted advantage on resistance of the relaxation of the cast iron in which graphite is contained in globular form [68, 106]. It is characteristic that when, in the structure, spheroidal graphite is present, the relaxation resistance of cast iron to considerably smaller degree depends on the character of metal base. It is interesting also to note that the relaxation resistance of pearlitic nodular cast iron 2 (at 450°C) approximately the same as in cast steel of brand 25L. This is evident from the comparison of the values of the remaining stress for both materials in identical ratio $\sigma_0/\sigma_{0,2}$ (Fig. 92).

Great effect on the relaxation resistance of metals and alloys

(as generally for heat resistance) has the size of the grain of basic solid solution. B. M. Rcvinskiy and V. G. Ljuttsa [12, s. 35] studied the effect of this factor on copper and aluminum at room temperature. The size of the grain of the metals being investigated varied from 0.01 to 2.2 mm. Testing carried out employing the proposed by the authors procedure, described above (see Chapter III). It is established, that the so-called "index of relaxation compliance/pliability" increases with an increase in grain size. Consequently, the relaxation resistance is higher, the lesser grain. It should be noted that these data were obtained for 20°C and insignificant duration of tests.

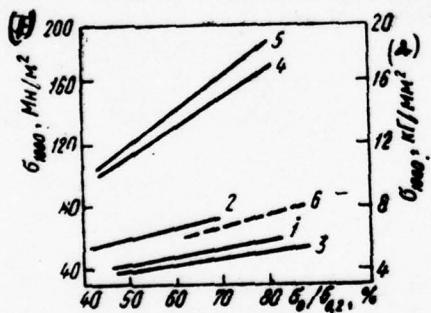


Fig. 92. Dependence σ_r after 1000 h with 20°C on ratio/relation $\sigma_0/\sigma_{0.2}$ for cast iron (1-5) (see Table 36) and cast steel 25L (6) [106].

Key: (1). MN/m². (2). kg/mm².

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On other data [186], the specimen/samples of copper with the size of grain 0.03 and 0.18 mm showed virtually identical relaxation life for 90 h with 20°C, but metal with coarser grain had certain advantage with 150-200°C.

Interesting results are obtained by M. L. Khenkin and N. K. Levinoy [186] on ferrosilicon (30% Si) with the size of grain 0.033 and 0.244 mm. As can be seen from the primary curves of relaxation (Fig. 93), at 20°C definite advantage has fine-grained material, but at 200°C it becomes less noticeable, but at 400°C coarse-grained material prove to be itself more preferably on relaxation resistance. Analogous results were obtained by the same authors at 20 and 400°C for low-carbon steel.

Most in detail the effect of grain size on the relaxation resistance of the unalloyed pearlitic steel (0.17% C) was studied by T. I. Volkovoy. Different size of grain (from point 8 to 2) was reached by annealing at 1050°C during 1; 5; 20 and 80 h.

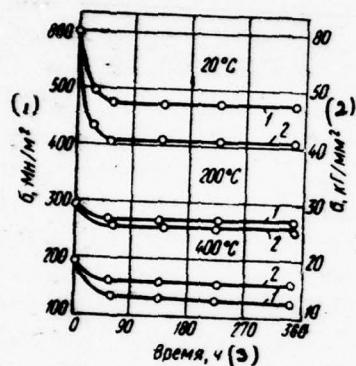


Fig. 93.

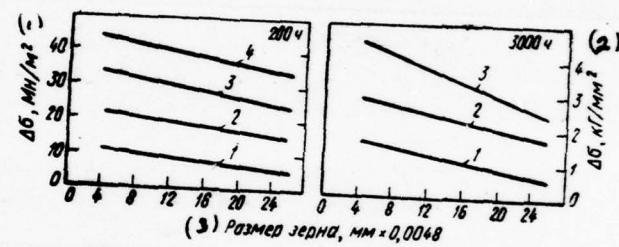


Fig. 94.

Fig. 93. Curves of relaxation of ferrosilicon (30% Si) with size of grain 0.033 (1) and 0.244 mm (2).

Key: (1). MN/m^2 . (2). kg/mm^2 . (3). Time, h.

Fig. 94. Effect of grain size they became 20 to value $\Delta\sigma$ at 400°C and σ_0 , MN/m^2 (kg/mm^2) [92, p. 74]: 1 - 30(3); 2 - 70(7); 3 - 100(10); 4 - 120(12).

Key: (1). MN/m^2 . (2). kg/mm^2 . (3). size of grain, $\text{mm} \times 0.0048$.

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Relaxation tests at 300 and 400°C by duration to 3000 h showed that with an increase in grain size value $\Delta\sigma$ is decreased (Fig. 94), which indicates an increase in resistance of relaxation. In this case, most noticeable effect coarsening exerts in relaxation time [92, s. 74].

V. Z. Tseytlin [18] showed, that an increase in the temperature of normalization of low-alloy steel 25Kh1MFA and 30KhMA from 880-920 to 1000°C considerably increases their relaxation life: by the first - at 400-500°C, by the second - at 500-550°C. This effect the author explains by a considerable increase in grain sizes during heating under standardization to 1000°C. At the same time it is known that low-alloy steel, used for springs, that work at room and close to it temperatures, possess the best relaxation life after the heat treatments, which ensure fine-grained structure [142].

It is necessary to consider the temperatures, at which are obtained the experimental data. Apparently, at different temperatures grain size affects differently - similarly how this is observed under conditions of creep.

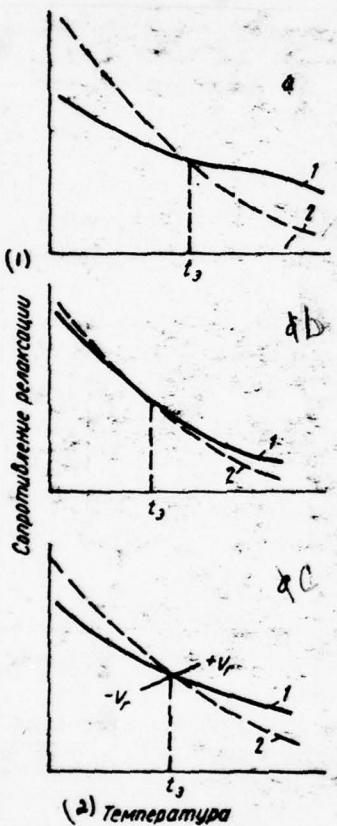


Fig. 95. Diagram of temperature effect on resistance of relaxation of stresses of coarse-grained (1) and fine-grained (2) steel: a - in I relaxation time; b - in II period; c - total curves.

Key: (1). Resistance of relaxation. (2). Temperature.

With an increase in grain size, resistance of the alloy of creep to certain temperature falls, then it increases. This is connected with a change in the relative strength of the material of grain itself and border regions in dependence on temperature [18]. In the literature are given different interpretations of this phenomenon, including from crystallographic and dislocation positions [187, 188]. The temperature, at which coarse-grained metal becomes stronger than the fine-grained, was called "equicohesive" or "uniformly strong".

Stress relaxation, just as creep, lower than equicohesive temperatures t_e will occur/flow/last less intense at fine-grained structure, but is higher than this temperature - with coarse-grained (Fig. 95). At equicohesive temperature the effect on relaxation of stresses of the intergranular and intragranular processes, which determine the advantage of the other one or structure, approximately is equal.

The rate of relaxation v_r (as creep rate v_m) affects equicohesive temperature t_e . At high rates of relaxation, level t_e is increased, with small ones, on the contrary, it descends. The effect of the rate of relaxation on the position of point t_e is shown on Fig. 95c.

Unlike creep, the effect of grain size under conditions of stress relaxation is developed predominantly in initial period. The

ccmparison of the first and second sections of the primary curves $\sigma-\tau$, obtained for one and the same material with different grain size, shows noticeably the larger difference between the relaxation of large and fine-grained material in the first relaxation time, than in the secnd.

Therefore the dependence of resistance of the relaxation of large and fine-grained material on temperature should be examined for two relaxation times separately (see Fig. 95). In accordance with the noted above dependence of equicohesive temperature on the rate of relaxation point t_0 in Fig. 95c in comparisn with diagram a is moved into the region of higher temperature.

Thus, for an increase in the relaxation resistance of alloys at relatively high temperatures, in particular with the limited period of their service, is expedient an increase in the size of the grain of basement structure; in connection with this all forms of the heat treatment, which lead to coarsening, are preferable ones.

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However, coarsest grain almost unavoidably leads to the considerable decrease of prolonged plasticity and in a series of cases contributes to sensitivity to stress ccncentrators. Therefore excessively coarse

grain in the metal of fasteners is inadmissible. So, as optimum is recommended grain from the 3rd to the 6th point for pearlitic steel and from 3 to 5 - for austenitic ones [13, 24; 92, s. 74]. Analogous recommendations for nonferritic alloys in the literature it is not brought.

Of the considerable category of alloys, first of all to austenitic steels and alloys, is intrinsic heterogranularity. On sharp deterioration in the creep strength of alloys with heterogranular structure, there are convincing data [160, s. 228; 189]. It is possible to assume the analogous effect of heterogranularity, also, under conditions of stress relaxation, although the direct/straight experimental data, which confirm this until published.

2. Effect of heat treatment on the relaxation resistance of austenitic steels and of alloys.

The most widely used version of the heat treatment of heat-resistant dispersive hardening austenitic steels is the two-stage treatment, which includes: quenching (austenitizing) from the temperature, which ensures obtaining moderately coarse grain of austenite and stabilizing tempering at temperature on 50-150 deg higher than the worker. The role of the size of the grain of basement

structure and dispersed isolation of excess phase was examined in detail above.

during the development of the concrete, specific/actual conditions/modes of the heat treatment of austenitic steels, intended for high-temperature service under conditions of relaxation of stresses or creep, one should consider the tendency of the datum of steel toward age hardening and the individual characteristics of the course of this process at operating temperature.

It is necessary to specify, which precisely should understand by "tendency toward age hardening". One of the methods of estimating this property is instituted on the account to the degree of strengthening steel as a result of dispersive to consolidation". One of the methods of estimating this property is instituted on the account to the degree of strengthening steel as a result of age hardening.

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Most frequently here is utilized an increase in the hardness (less frequent - the limit of strength and yield) or a reduction in the impact toughness. These indirect criteria especially widely were applied and they were only) before the development of phase chemical

analysis. But there is nowhere concrete/specific/actual recommendations, during what (absolute or relative) increase in the hardness or σ_8 and $\sigma_{0.2}$ should count austenitic steel strongly or weakly dispersive hardening.

To it is considerably more right estimate the tendency of austenitic steels toward age hardening according to a quantity of releasing phase. Austenitic steels in which a quantity of strengthened/hardened phase in structure (after the optimum conditions/modes of age hardening) does not exceed 1-2%, usually consider as weakly dispersive hardening; they became with 10% of phase and more - strongly hardening; they became, the containing 3-8% second phases, moderately hardening. The given gradations are very conditional ones.

With the reference of austenitic steel to one or the other category, it is necessary to also consider the intensity of the process of age hardening, i.e., kinetics of the isolation of secondary phases from solid solution. The incubation period of the isolation of phases can be different - from several minutes to thousand and more than hours - depending, on the chemical composition of the phase and basic solid solution, temperature and other factors [18, 183].

The advisability of the operation of the stabilizing tempering is caused by the special feature/peculiarities of the course of the process of age hardening. Sc, for weakly dispersive hardening austenitic steels tempering is optional, since it is not virtually changed relaxation resistance. In strong and average dispersive hardening steels the character of the effect of tempering is determined by the relationship/ratio of the temperatures of tempering and testing, and also by their relative attitude in the range of temperatures of age hardening.

At operating temperatures, that are located between the bottom and optimum temperatures of age hardening, the resistivity of relaxation is above in tempered steel, if tempering temperature only insignificantly differs from optimum worker.

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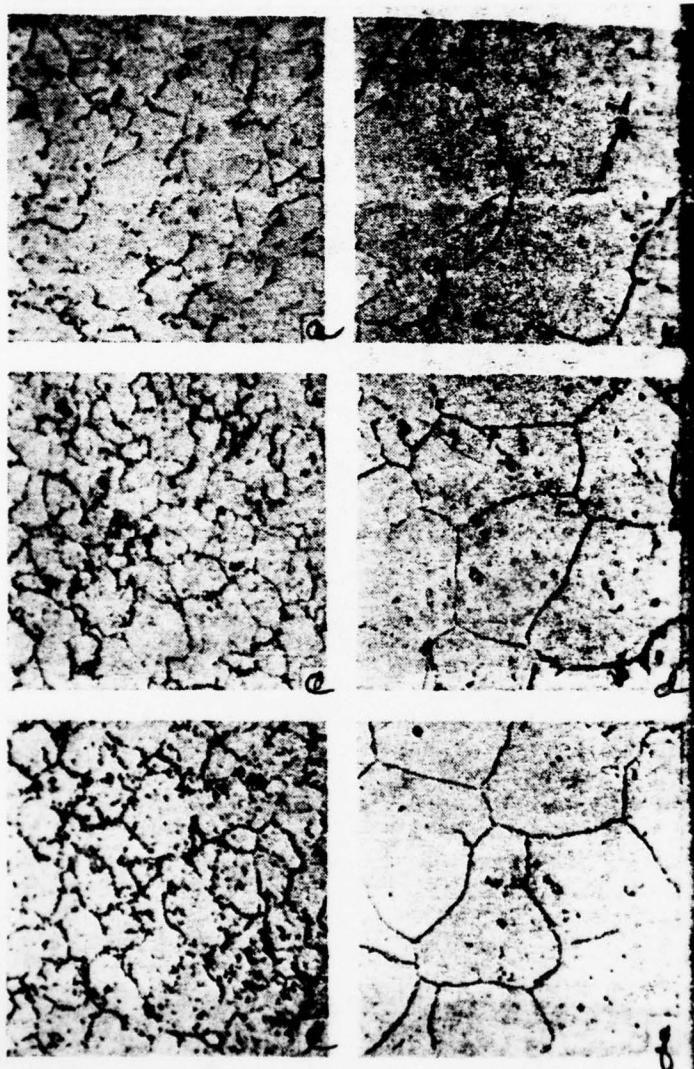


Fig. 96. The microstructure of austenitic steels X200: a - steel 1Kh18N9T, tempering with 1050°C; b - the same, with 1200°C; c - 1Kh14N18V2BR, quenching with 1000°C. d - the same, with 1250°C; e -

Kh20N25VM3B, quenching with 1000°C; 1 - the same, with 1200°C.

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Tempering at the temperatures, close to upper boundary of age hardening or exceeding it, on the contrary, the voltage dropping resistor of relaxation. At operating temperatures, which are located between the optimum and upper temperature of age hardening, resistance of relaxation in tempered and not tempered steel can be identical, if tempering is produced at relatively low temperature.

Finally, if operating temperature exceeds the upper boundary/interface of age hardening, tempering hardened steel at any temperature cannot raise its prolonged heat resistance and relaxation resistance.

Let us examine the effect of the heat treatment of steels 1Kh18N9T, 1Kh14N18V2BR and Kh20N25VM3B, which relate to weakly and average dispersive hardening austenitic steels and which are distinguished by the degree of alloying of solid solution and by type of secondary phases.

In hardened state these steels have the polyhedral structure of solid solution (Fig. 96) and they possess lower hardness and

strength, but high plasticity. During tempering the hardness and strength are increased (see Table 38), and plasticity is decreased mainly because of precipitation of excess phases. The common/general/total content of excess phases (in the hardened/tempered and tempered state) in steel Kh20N25VM3B is somewhat higher than in the others (2-3% against 0.8-1.5%).

Table 38. Hardness of austenitic steels after heat treatment.

(1) Сталь	(2) Темпера- тура за- калин., °C	(3) Твердость HB после отпуска при температуре			(4) Продол- житель- ность отпуска, ч
		(5) без от- пуска	750°C	800°C	
Х18Н9Т	1050 1200	156 143	168 143	170 156	12 12
ХН18В2БР (1695р)	1000 1250	156 131	168 149	170 156	16 16
ХН25ВМ3Б (1148)	1000 1200	187 168	197 187	229 197	24 24

Key: (1). Steel. (2). Temperature of quenching, °C. (3). Hardness HB after tempering at temperature. (4). Duration of tempering, h. (5). without tempering.

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Was studied the temperature effect of quenching and tempering on

the relaxation resistance of steels [190] indicated.

Prolonged relaxation test (by circular method) carried out with 650°C and initial stresses 60-200 MN/m² (6-20 kg/mm²). The basic results, presented in Table 39, testify to different intensity of stress relaxation after the applied conditions/modes of heat treatment.

Quenching from higher temperatures (1200-1250°C) at any temperature of tempering (or without it) leads to the higher level of the remaining stresses with 650°C, than quenching from relatively low temperatures (1000-1050°C). However, for steels 1Kh18N9T and Kh14N18V2 the difference in the value of the remaining for 1000 h stress is not so/such great - it composes 10-20% in hardened state and to 25% in that tempered (Table 39). In steel Kh20N25VM3B, this difference is noticeably more, namely 25-30% after quenching and 25-80% after quenching and tempering.

Tempering steel Kh14N18V2B (at the same temperatures) in accordance with what has been said does not above affect positively the process of stress relaxation. Value σ_{1000} for this steel in comparison with hardened state even is decreased (by 20-25%, Table 39).

Tempering steel Kh20N25VM3B with 750-800°C substantially decreases the intensity of relaxation of stresses with 650°C. An increase of σ_{1000} in fine-grained steel (harden/tempered with 1000°C) reaches to 40%, and in coarse-grained (harden/tempered with 1200°C) - to 55% (see Table 39). The effect of tempering on the relaxation resistance of this steel is clearly evident in the primary curves of relaxation (Fig. 97).

If austenitic dispersive hardening steel is subjected to the heat treatment, which leads to the formation of coagulated particles of the excess phase, then its relaxation life will be noticeably lowered. This is evident based on the example of steel Kh15N25V4T (Table 40), tested for the relaxation whose high-temperature tempering leads to the coagulation of the particles of the intermetallic phase.

The preliminary thermal holding of high cf duration with the worker or close to it temperatures actually can be considered as very prolonged tempering at the appropriate temperatures.

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(1) режим термической обработки	(2) $\sigma_0.1$, M_N/m^2 ($\kappa\Gamma/mm^2$)	(3) σ_t , M_N/m^2 ($\kappa\Gamma/mm^2$) стаей		
		1X18H9T	1X14H18B2БР	X20H25ВМ3Б
(4) акалка с 1000— 1050°C	60(6)	<u>23(2,3)</u> 15(1,5)	<u>31(3,1)</u> —	—
	100(10)	<u>43(4,3)</u> 27(2,7)	<u>48(4,8)</u> 36(3,6)	—
	150(15)	<u>58(5,8)</u> 49(4,9)	<u>75(7,5)</u> 67(6,7)	<u>41(4,1)</u> 23(2,3)
	200(20)	—	—	<u>45(4,5)</u> 43(4,3)
(5) то же+отпуск при 750°C	60(6)	<u>25(2,5)</u> 18(1,8)	<u>26(2,6)</u> 20(2,0)	—
	100(10)	<u>36(3,6)</u> 28(2,8)	<u>43(4,3)</u> 37(3,7)	—
	150(15)	<u>68(6,8)</u> 58(5,8)	<u>65(6,5)</u> 52(5,2)	<u>42(4,2)</u> 25(2,5)
	200(20)	—	—	<u>67(6,7)</u> 52(5,2)
(6) то же+отпуск при 800°C	60(6)	<u>30(3,0)</u> 24(2,4)	<u>29(2,9)</u> 18(1,8)	—
	100(10)	<u>51(5,1)</u> 43(4,3)	<u>47(4,7)</u> 39(3,9)	—
	150(15)	<u>70(7,0)</u> 60(6,0)	<u>68(6,8)</u> 56(5,6)	<u>39(3,9)</u> 26(2,6)
	200(20)	—	—	<u>75(7,5)</u> 60(6,0)

1 Закалка с 1200— 1250° C	60(6,0)	<u>25(2,5)</u> 17(1,7)	—	—
	100(10)	<u>46(4,6)</u> 30(3,0)	<u>55(5,5)</u> 44(4,4)	—
	150(15)	<u>75(7,5)</u> 59(5,9)	<u>84(8,4)</u> 71(7,1)	<u>43(4,3)</u> 36(3,6)
	200(20)	—	—	<u>59(5,9)</u> 53(5,3)
2 То же+отпуск при 750° C	60(6)	<u>29(2,9)</u> 21(2,1)	<u>31(3,1)</u> 24(2,4)	—
	100(10)	<u>47(4,7)</u> 39(3,9)	<u>44(4,4)</u> 36(3,6)	—
	150(15)	<u>81(8,1)</u> 65(6,5)	<u>68(6,8)</u> 56(5,6)	<u>63(6,3)</u> 40(4,0)
	200(20)	—	—	<u>80(8,0)</u> 65(6,5)
3 То же+отпуск при 800° C	60(6)	<u>35(3,5)</u> 30(3,0)	<u>34(3,4)</u> 29(2,9)	—
	100(10)	<u>59(5,9)</u> 48(4,8)	<u>57(5,7)</u> 45(4,5)	—
	150(15)	<u>83(8,3)</u> 70(7,0)	<u>78(7,8)</u> 65(6,5)	<u>68(6,8)</u> 52(5,2)
	200(20)	—	—	<u>100(10)</u> 84(8,4)

Key: (1). Conditions/mode of heat treatment. (2). MN/mm² (kg/mm²). (3). MN/mm² (kg/mm²)¹ of steels.

FOOTNOTE¹. In numerator - after 1000 h, in denominator - after 2000 h. ENDFOOT NOTE.

(4). Tempering with 1000-1050°C. (5). The same+tempering at 750°C.

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In work [167] were studied structural transformations in the process of prolonged thermal holding at temperatures of 500-800°C of austenitic steels of brands Kh18N9, Kh18N9T, 1Kh14N14V2M, 4Kh14N14V2M, Kh20N25, 4Kh18N25S2, Kh14N14V2 and alloys KhN35VMT and Kh15N60.

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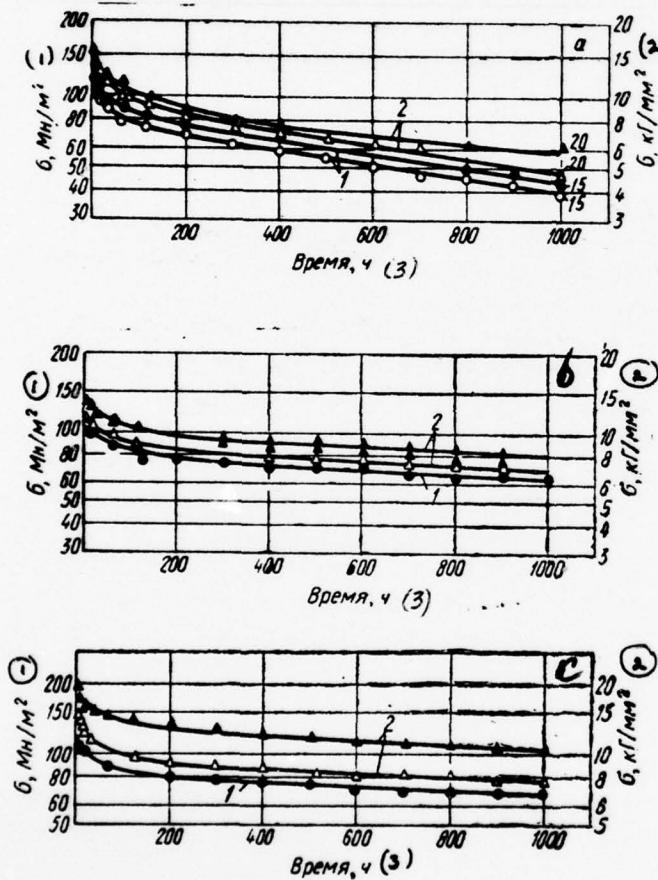


Fig. 97. Relaxation curves of steel Kn20N25VM3E with 650°C; a - quenching with 1000°C (bright marks) and with 1200°C (dark); b - the same+tempering at 750°C; c - the same+tempering at 800°C; σ_0 MN/m²

(kg/mm²: 1 - 150 (15); 2 - 200 (20).

Key: (1). MN/m². (2). kg/mm². (3). Time, h.

[Page 266.] By L. B. Getscv and M. G. Taubincy [191] is investigated the effect of thermal holding by duration 5000=10,000 h (and sometimes - to 50,000 h) on creep strength with 600-800°C austenitic steels Kh23N18, 3Kh19N9MVBT, 4Kh12N8G8MEE and alloys of KhN35VTYu. A. F. Zlepko [192] cite data on the effect of thermal holding by duration to 30,000 h on stress-rupture strength with 600°C of austenitic steels Kh18N12T, Kh14N18V2BR and 4Kh14N14V2a.

In the enumerated works it is established, that the preliminary prolonged heating at the temperature of subsequent creep test (or with higher) leads to a considerable reduction in the creep strength, i.e., to the increase of creep rate and the decrease of time to rupture with this stress ¹.

FCCTNOTE ¹. In more detail about structural changes transformations in austenitic steels with prolonged holding stated in monograph [18].
ENDFOOTNOTE.

On the basis presented in Chapter II it is possible to expect the analogous effect of prolonged holding and under conditions of stress

relaxation.

The negative effect of prolonged thermal holding on the heat-resistant properties of steel is connected with the decrease of the degree of alloying of solid solution and with the coagulation of the particles of the excess phase whose value up to the torque/moment of loading, will be more than after common short-term tempering.

The relaxation resistance of heat-resistant nickel base alloys (so, as austenitic steels) is determined by the size of the grain of solid solution, by the degree of its alloying (changing depending on temperature quenching); by type, by quantity and degree of dispersion of the excess phases, which separate during tempering.

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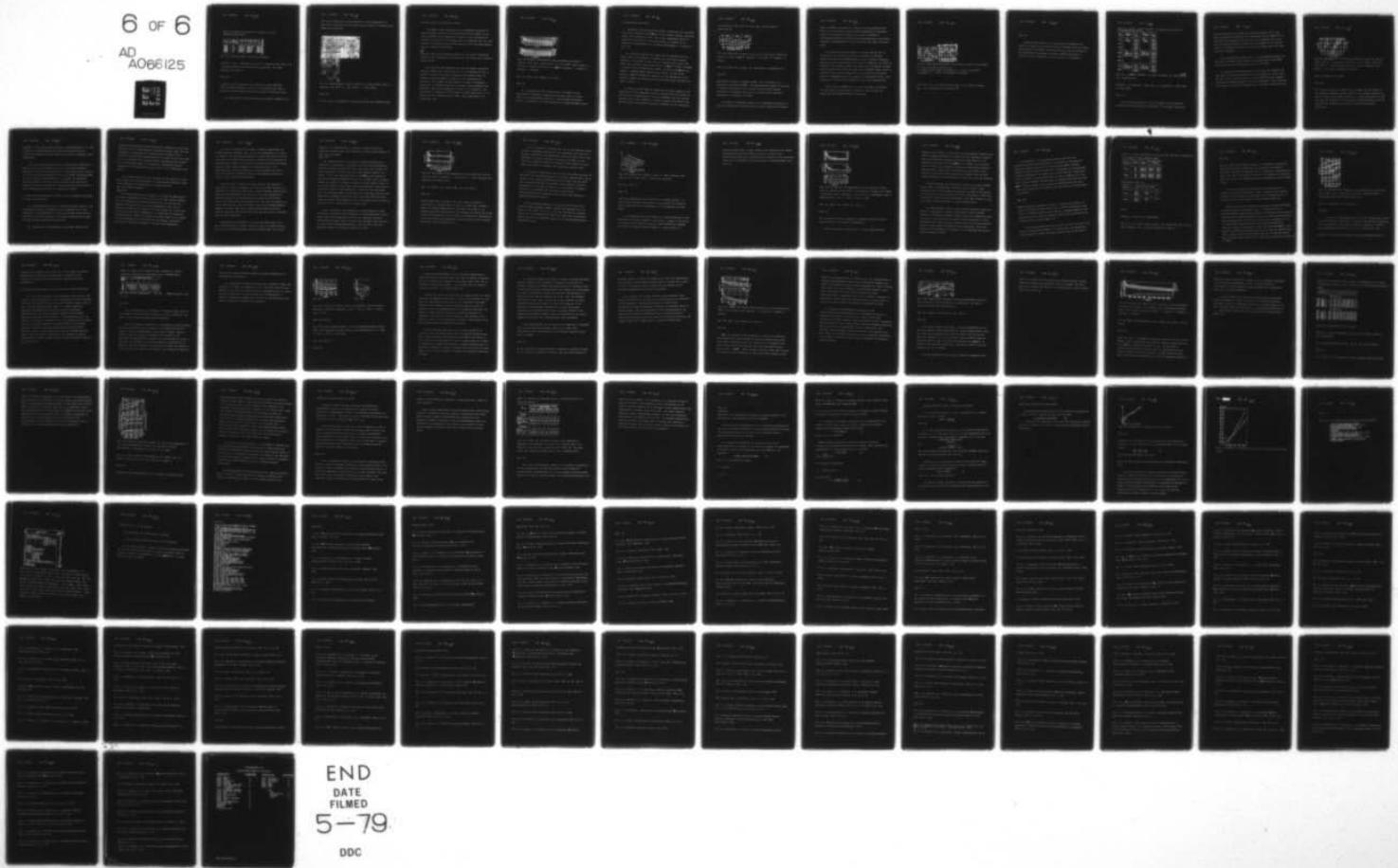
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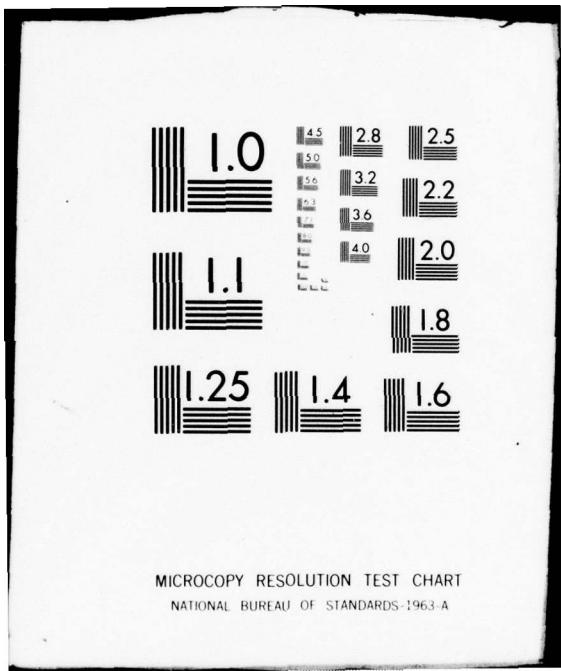


Table 40. Remaining stresses of relaxation in steel
Kh15N25V4T with 650°C.

$\sigma_0, \text{ MN/m}^2 (\text{kg/mm}^2)$ (1)	Термическая обработка ²	$(2)\sigma_t, \text{ MN/m}^2 (\text{kg/mm}^2)$, за время, с		
		120	500	1000
200(20)	З+о.	170(17,0)	166,5(16,65)	162(16,2)
200(20)	В.о.	145(14,5)	136(13,6)	112(11,2)
250(25)	З+о.	214(21,4)	2075(20,75)	202(20,2)
250(25)	В.о.	180(18,0)	155(15,5)	140(14,0)
300(30)	З+о.	261(26,1)	232(23,2)	220(22,0)
300(30)	В.о.	237(23,7)	209(20,9)	150(15,0)

Key: (1) . MN/m² (kg/mm²) . (2) . Heat treatment¹.

FCOTNOTE¹. Z+о. - quenching with 1130°C + tempering with 750°C. В.о.
- high-temperature tempering (without quenching). (3) . MN/m²
(kg/mm²), for time, h.

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A quantity of such phases in the structure of heat-resistant nickel-chromium alloys, as a rule, is considerably more than in austenitic nickel-chromium steel (it composes 10-20% and more).

For the majority of the nickel-chromium alloys, intended for a

work under conditions of high-temperature stress relaxation, is applied the two-stage heat treatment, which consists of quenching and stabilizing tempering.

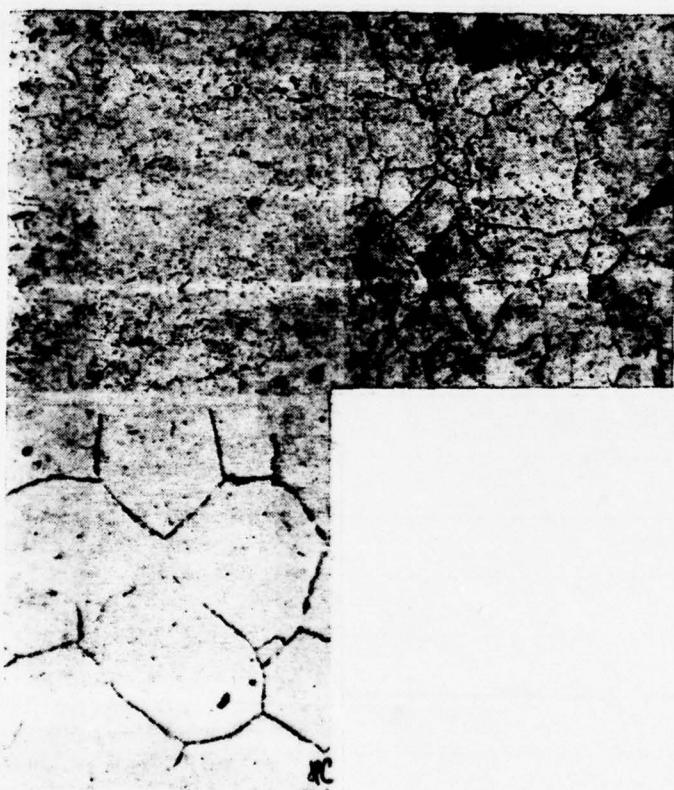


Fig. 98. Microstructure of alloy KhN77Tyu in initial state. X200: a - quenching with 950°C; b - with 1080°C; c - with 1150°C.

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In this case, the tendency of such alloys toward age hardening plays

the same role, as in austenitic steels.

The effect of heat treatment on the relaxation resistance of nickel-chromium alloys let us examine based on the example of the alloy KhN77TYu. It is strengthened because of the intermetallide compound Ni₃ (Ti, Al) (γ' - phase), which is separated from the solid solution in quantity 8-13% during heating of the hardened/tempered alloy in interval of 650-800°C.

4P
Quenching effect and temperings studied in the metal of industrial melting of the composition: 0.05% C; 2.0% CR; 2.5% Ti; 0.75% Al (other nickel).

With quenching intermetallide Ni₃ (Ti, Al) almost completely transfer/converts into solid solution; in the undissolved state it remains a total of 1-1.5% of intermetallic compound phase. In connection with this with an increase in the temperature of quenching, the hardness and the strength of alloy is decreased, plasticity is improved, grain sizes increase. After quenching with 950-960°C, grain size corresponds to point 7; an increase in the temperature of quenching to 1050-1080°C increases grain size to 3-4 points, and with quenching with 1150°C, grain grows/rises to 2-1 points (Fig. 98).

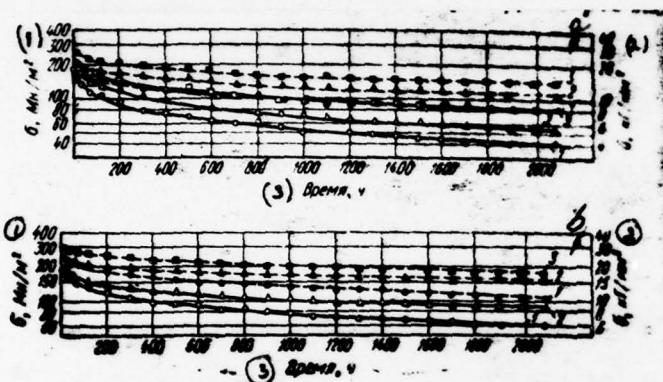


Fig. 99. Curves of relaxation of alloy KhN77TYu with 650°C: a - quenching with 950°C (bright marks) and with 1080°C (dark marks); b - the same + tempering with 750°C; σ_0 , MN/m² (kg/mm²): 1 - 250(25); 2 - 300(30); 3 - 350(35).

Key: (1). MN/m². (2). kg/mm². (3). Time, h.

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It is necessary to bear in mind, that an increase in the temperature of quenching, besides grain-growth, leads to certain change in the subgranular structure of alloy (mosaic structure). However, its effect on the heat resistance of nickel-chromium alloys

is relatively small [193].

Relaxation tests (by circular method) carried out with 650-700°C and initial stresses 100-300 MN/m² (10-30 kg/mm²). Primary relaxation curves are represented in Fig. 99, and the temperature effect of quenching on the value of the final stress σ_r , accepted by the fundamental characteristic of relaxation resistance, it is shown on Fig. 100.

The dependence between the temperature of quenching and the final stress of relaxation is expressed by curves with slanting maximum. As is evident in Fig. 100, the maximum value σ_γ for time 1000, 2000 and 3000 h with $\sigma_0=100$ and 150 MN/m^2 (10 and 15 kg/mm²) is observed after quenching with 1050°C, but with $\sigma_0=200 \text{ MN/m}^2$ (20 kg/mm²) - probably after quenching with 1080°C. In this case, a change in value σ_r during the variation of the temperature of the quenching within the limits indicated relatively small and does not exceed 25-30%.

It should be noted that the dependence of creep strength on the temperature of the quenching of alloys KhN77Tyu [195] and nimonic 90 [196] (close in composition to the alloy KhN77Tyu) also has extreme character (Fig. 101). However, a relative change in the value of the initial stress of relaxation during the variation of the temperature

of quenching is less than the creep rate v_m or of time of decomposition.

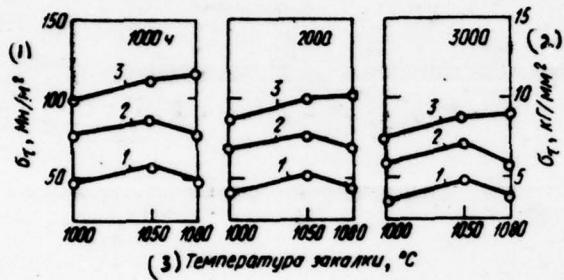


Fig. 100. Temperature effect of quenching on value σ_r at 700°C and different values σ_0 , MN/mm² (kg/mm²): 1 - 100(10); 2 - 150(15); 3 - 200(20).

Key: (1). MN/mm². (2). kg/mm². (3). Temperature of quenching, °C.

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Furthermore, maximums in curves $\sigma_r - t_{\text{quench}}$ for low values σ_0 in comparison with curves $\tau_0 - t_{\text{quench}}$ are insignificantly moved to the side of smaller temperatures. But at higher initial stress maximum resistance of relaxation and creep is achieved at the identical temperature of quenching of 1080°C.

The effect of tempering (aging) on the relaxation resistance of alloy was studied after quenching from optimum temperature indicated

above of 1080°C, and also for a comparison after quenching with 950°C. As it was noted, the last/latter temperature of quenching leads to fine-grained structure and it was of interest to reveal/detect/expose the special feature/peculiarities of secondary structural transformations in solid solution with small and coarse grain.

From primary curves the stress - the time (see Fig. 99) is evident that the intensity of stress relaxation is different depending on the used conditions/mode of heat treatment. Tempering (aging) increases resistance of the alloy of relaxation (at 650°C) in comparison with hardened state. The values of the remaining stresses after tempering with 750°C are higher than afterward 800°C, which is connected with certain "cveraging" of alloy with the last/latter version of tempering. The total quantity of γ' -phase in alloy, after tempering at 750 and 800°C composes 9.0 and 8.0% respectively.

From the data of Table 41, it is not difficult to calculate, that the values σ_{1000} because of tempering can be raised (in comparison with hardened state) to 50-650/c.

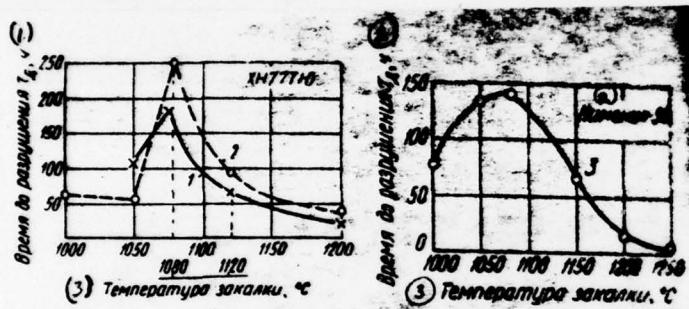


Fig. 101. The temperature effect of quenching on time to the failure of alloys KhN77TYu and Nimonic-90:
1 - $t=600^{\circ}\text{C}$, $\sigma=600 \text{ MN/m}^2$ (60 kg/mm^2); 2 - $t=700^{\circ}\text{C}$; $\sigma=360 \text{ MN/m}^2$ (36 kg/mm^2); 3 - $t=750^{\circ}\text{C}$; $\sigma=300 \text{ MN/m}^2$ (30 kg/mm^2).

Key to Fig. 101. (1). Time to failure τ_A , h. (2). Time to failure τ_A , h. (3). Temperature of quenching, °C.

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Quenching with 1080°C at any temperature of tempering (or without it) leads to considerably higher relaxation life with 650°C, than quenching with 950°C. The values of σ_{1000} with an increase in the temperature of quenching from 950 to 1080°C grow/rise: in hardened state to 75-100%, in that tempered - to 50-100%.

Table 41. Effect of heat treatment on relaxation resistance of alloy KhN77TYu at 650°C.

(1) σ_0 MН/m ² кГ/мм ²	(2) Термическая обработка	(1) σ_{τ}^t . MН/m ² (кГ/мм ²)	(2) Термическая обработка	(1) σ_{τ}^t . MН/m ² (кГ/мм ²)
250(25)	(3) Закалка с 950°C	50(5,0) 40(4,0)	(3) Закалка с 1080°C	98(9,8) 82(8,2)
300(30)		69(6,9) 54(5,4)		126(12,6) 102(10,2)
350(35)		95(9,5) 80(8,0)		156(15,6) 140(14,0)
250(25)	(3) Закалка (4) с 950°C + от- пуск при 750°C	75(7,5) 52(5,2)	(3) Закалка с (4) 1080°C + от- пуск при 750°C	128(12,8) 106(10,6)
300(30)		104(10,4) 88(8,8)		173(17,3) 150(15,0)
350(35)		—		197(19,7) 170(17,0)
250(25)	(3) Закалка с (4) 950°C + отпуск при 800°C	54(5,4) 42(4,2)	(3) Закалка с (4) 1080°C + от- пуск при 800°C	104(10,4) 85(8,5)
300(30)		107(10,7) 90(9,0)		148(14,8) 130(13,0)

Key: (1). σ_0 , MN/m² (kg/mm²). (2). Heat treatment. (3). Quenching ^(with)
(4). tempering with.

FOOTNOTE 1. In numerator - after 1000 h, in denominator - after 2000
h. ENDFOOT NOTE.

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Most visually the effect of heat treatment on the relaxation
resistance of alloy KhN77TYu is reflected on the graphs, which show

the interconnection of initial and remaining stresses (Fig. 102). These dependences confirm the vital importance of the temperature of quenching and tempering. From Fig. 102, it is possible also to see that the positive effect of tempering on the value of the remaining stress is relatively more with high initial stresses and it is less - with small stresses.

Thus, the maximum relaxation rate of alloy KhN77TYu provides the dual heat treatment, which consists of quenching with 1050-1080°C, with cooling in air and tempering for 10 h at 750°C.

The analogous conditions/modes of two-stage heat treatment are used also to the more complicatedly alloyed alloys. In recent years for such alloys in certain cases, are recommended the more complex (multistage) conditions/modes of the heat treatment, which facilitate an increase in their heat resistance and especially plasticity [197].

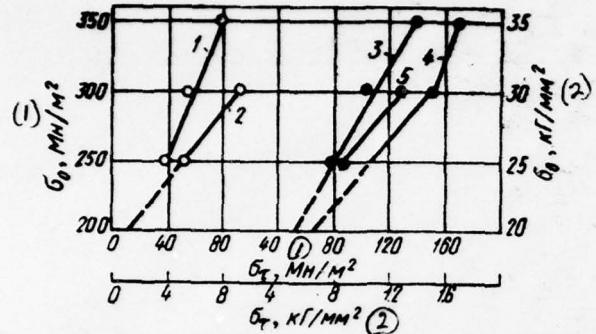


Fig. 102. Dependence $\sigma_t - \sigma_y$ for alloy Kn77TiYu at 650°C and time of testing 2000 h: 1 - quenching with 950°C ; 2 - the same + tempering with 750°C ; 3 - quenching with 1080°C ; 4 - also + tempering with 750°C ; 5 - the same + tempering with 800°C .

Key: (1) - MN/mm². (2) - kg/mm².

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The numerous versions of complex heat treatments can be reduced to the following diagrams: a) dual quenching with common tempering; b) graded hardening with common tempering; c) common quenching with dual (or repeated) relaxation; e) the combined treatment during which the quenching and tempering are conducted under the complicated conditions¹.

FOOTNOTE 1. The concrete, specific/actual conditions/modes of the heat treatment of nickel-chromium heat-resistant alloys and their theoretical substantiation are examined in detail in monograph [18].
ENDFOOTNOTE.

Since the nickel-chromium alloys, utilized under conditions of highly temperature relaxation, as a rule, they have sufficient plasticity and they are insensitive to stress concentrators, there is no need for the application/use for them of complex conditions/modes of heat treatment. The advisability of applying the multistage treatment should be solved in each individual case, taking into account in this case considerable complication and rise in price of the technological process of the production of parts.

3. Effect of thermomechanical treatment on the relaxation resistance of steels and of alloys.

The thermomechanical working of metals and alloys, which is the combination of plastic deformation (work hardening) and of heat treatment, is the progressive technological process, which makes it possible to increase the level of mechanical properties they began and other alloys, including heat-resistant.

The possibility of strengthening the metallic alloys by the

combination of mechanical and precipitation hardening was noted into 1943 more in S. T. Konoteyevskiy's theoretical works [198]. The real possibility of applying the thermomechanical treatment for an increase in the heat-resistant properties is shown for the first time by V. D. Sadovskiy with colleagues [199]. Subsequently was carried out a considerable number of experimental investigations whose comprehensive survey/coverage can be found in M. L. Bernstein's work [200].

The numerous methods of this treatment can be referred to three basic forms: NTMO (low-temperature thermomechanical treatment), VTMO (high-temperature thermomechanical treatment) and MTC (mechano-thermal treatment).

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The diverse variants these treatments connect the operations of the plastic deformation which carry out at the most diverse degrees of the deformation and different temperatures, and strictly heat treatment basic parameters of which (temperature, time, rate of heating and cooling) can oscillate over wide limits. As a result are obtained the most varied combinations of mechanical work hardening, recrystallization, return and aging whose total effect on the process of stress relaxation can be differently and depends, furthermore, from specific operating conditions - duration and temperature.

At room, the reduced and moderate, elevated temperatures any thermomechanical treatment (just as cold work hardening), as a rule, it increases the relaxation resistance of metals and alloys. This are explained by the fact that TMC leads to creation in the structure of polysrystalline metall of the evenly distributed internal dislocation barriers, which prevent movement of dislocation [22, s. 65]. Simultaneously increases dislocation density, moreover the latter after NMTM (with the identical degree of deformation) almost by an order is higher than after VTMC [200].

Positive effect of TMC can be shown based on the example of low-alloy steel 35GS, investigated in work [201]. VTMC consisted in deformation to 30% with 900°C with by those following quenching and tempering. Relaxation test was carried out at room temperature by circular method, at the sufficiently high values of the initial stress: 950, 1200, 1400 and 1600 mN/mm² (95, 120, 140, 160 kg/mm²). As can be seen from Fig. 103, the voltage drop in the specimen/samples, subjected to VTMC, less than in those harder/tempered and those tempered specimens. This law is valid both for the initial relaxation time and after 200-400 h.

Furthermore, from findings it follows that VTMC leads to the more stable structure of steel: anomalous peaks (on initial section) curves for the hardened,tempered specimen/samples which the authors

explain by the decomposition of residual austenite and by the isothermal precipitation of carbon from solid solution, on curves, corresponding to VTMC, they are absent.

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The favorable effect of preliminary plastic deformation on resistance of relaxation in pearlitic steel at room and moderately elevated temperatures does not cause doubt. Thus, for example, the cold deformation of carbon steel with considerable reduction (to 80%), but the low initial voltage [$\sigma_0=40 \text{ MN/m}^2$ (40 kg/mm^2)] it increases relaxation resistance with 20% at 150°C , that to larger degree, the higher the content in steel of carbon (within limits of 0.3-0.9%). [142]. In this case, many authors indicate that there is an optimum degree of work hardening. As showed A. A. Krasil'nikov [41], this optimum amount of deformation for high steel U8A vary with temperature, composing 80% with 20°C ; 50% with 150°C and only 20% with 450°C . More detailed data on this question can be found in the book of V. Ya. Zubov and S. V. Glachev [97].

With an increase in the temperature on the process of stress relaxation, have effect such phenomena as recrystallization, return, aging. Under these conditions the decisive importance acquires time/temporary factor. After a certain time interval, which depends on temperature, strengthened/hardened action of TMO is lost and advantage obtains the material, subjected to TMC.

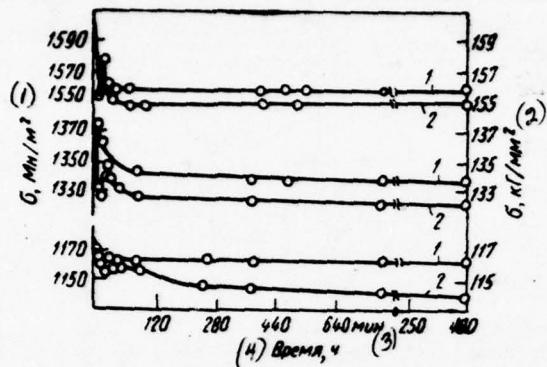


Fig. 103. The curves of the relaxation of steel 35GS with 20°C and different initial stresses: 1 - after VIMO; 2 - after quenching and tempering with 200°C [201].

Key: (1). MN/mm². (2). kg/mm². (3). min. (4). Time, h.

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Schematically this is shown on Fig. 104, where the points of intersection of straight lines for TMO and common heat treatment answer the maximum temperature of effective use of TMO at the assigned/prescribed service life. For example, if with the short-term loading (by duration of 10 h) of TMC it is effective at temperatures to t_5 , then during the elongation of service life to 1000 h maximum temperature will be lowered to t_3 .

If it is required to increase the time of the effective effect of TMO on relaxation resistance of this material, one ought not to approach excessively high dislocation density in metal, since such structural of state, obtained, for example, via NTMO, is with prolonged temperature effect is unstable. Better results it gives VTMO, which gives to somewhat less dislocation density [200].

For prolonged high-temperature service, as already mentioned in Chapter 1, was preferable polygonal structure. Polygonization can be created under certain conditions, also, with VTMO, and with NTMO, with the application/use of relatively small degrees of plastic deformation. In the case of NTMO for the formation of polygonal structure, is necessary the supplemental heat in the prerecrysallization temperature range, called some authors by recrysallization annealing.

Stable polygonal structure is obtained with the aid of the mechano-thermal treatment (MTO), proposed and developed by I. A. Eding and his school [21, 22, p. 65; 202]. This form of treatment consists in the deformation of metal to 1-10% with the specific temperature and the subsequent holding in the prerecrysallization temperature range.

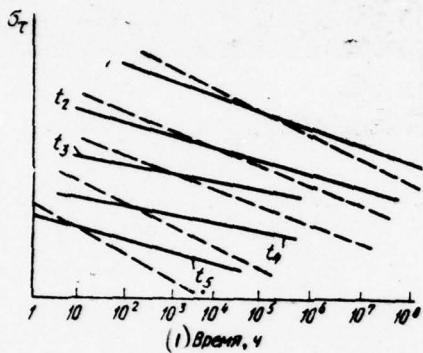


Fig. 104. Diagram of a change in value σ_r from relaxation time ($t_1 < t_5$): dash - TMO; solid - common heat treatment.

Key: (1). Time, h.

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Both these temperatures of deformation and thermal holding - in certain cases coincide. For example, during working of austenitic steel 1Kh18N9 for both operations it is recommended [21] with 600°C.

M. L. Bernsheyn and N. B. Libman [200] studied influence of TMO (according to diagram quenching - deformation - aging) on relaxation of stresses of the Ellinvar alloys of brands N41KhTA and N35KhMVA with 550°C and initial stresses $\sigma_0 \ll 0.8 \sigma_y$. During testing of

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specimen/samples made of alloy N41KhTA after quenching with 1000°C, deformation for 80/o and tempering during 0.5 and 5 h was establish/installled only an insignificant increase in the relaxation resistance in comparison with the undeformed specimen/samples (Fig. 105a, b).

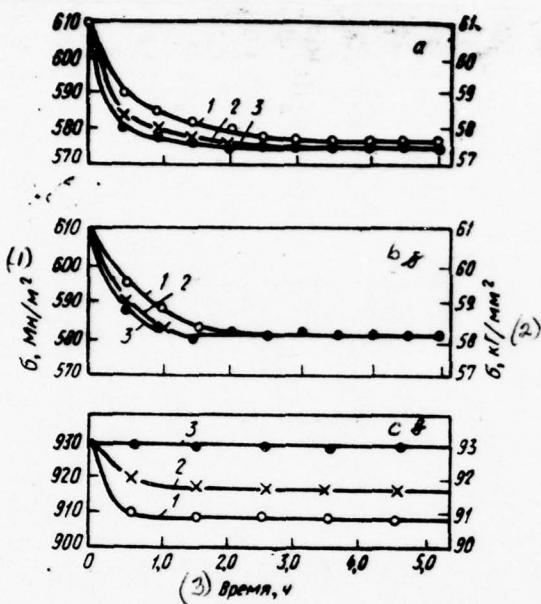


Fig. 105. The curves of the relaxation of alloy N41KhTA at 550°C [200]: a) quenching with 1050°C + tempering; b) the same, with 1000°C + deformation 80% + tempering; c) the same is, + deformation 140% + tempering with t , °C: 1 - 600; 2 - 700; 3 - 800.

Key: (1) • MN/m². (2) • kg/mm². (3) • Time, h.

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The temperature effect of tempering pronounced only at the quite initial moment of the process of relaxation.

Another picture was observed for the alloy, deformed after

quenching with 1000°C to 14c/o, when during subsequent tempering was formed polygonal structure. In connection with noticeable increase during the treatment of elastic limit indicated value of σ_0 in relaxation tests was led to 930 MN/m² (93 kg/mm²). As can be seen from Fig. 105c, the relaxation resistance of alloy also increased substantially, in particular after tempering with 800°C, which created in alloy this stable dislocation structure that at 550°C stress relaxation for this duration of tests not at all was observed.

Austenitic steels and nickel base alloys, as is known, possess large plastic deformability; therefore effect of TMO on their properties most is noticeable. For example, via VTMO it is possible to raise 100-h the stress-rupture strength of austenitic steels with 550-650°C to 15-25c/o [200]. Approximately the same increase in σ_{100} (to 20c/o) at 600°C gives MIC of steel 1Kh18N9T [21].

The effectiveness of TMO of heat-resistant austenite steels and alloys is confirmed by numerous investigations [200, 203-205]. However, in technical literature almost there is no information about the effect of TMO and MIC of austenitic steels and alloys on their relaxation life. There are only separate data on the application/use to them of cold plastic deformation (work hardening), which must affect their resistivity of relaxation in the same direction as the diverse variants of NTMC.

In particular, it is established, that the cold deformation (with the small degrees of reduction) of chrome-nickel austenitic steel of type 18-9 and 18-10 mark Kh18N19, Kh18N9T, Kh18N10, Kh18N10T improves resistance of relaxation at the moderately elevated temperatures ($\text{to } 400^\circ\text{C}$). So, in work [206] was investigated stress relaxation in the cold-worked wire with a diameter of 4.5 mm made of steel 1Kh18N9T with the limit of strength with 20°C 1450-1600 MN/mm 2 (145-160 kg/mm 2). The springs, manufactured from this wire, they showed satisfactory relaxation life with 385°C , but insufficient at $420-450^\circ\text{C}$.

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Initial stress was lowered: at 385°C by 44-47%, after 2500 h, at 420°C by 75.5-81.5% after 1750 h and at 450°C by 86-88.5% after 750 h. The absolute values of the remaining stresses (Table 42) are considerably lower than for analogous steel in the nonriveted state (compare with the data of Table 28).

On the cold-worked wire with a diameter of 3.8; 1, 9 and 1.5 mm from the same became 1Kh18N9T V. Ya. Zubov and L. A. Krasil'nikov [207] studied the effect of higher reduction (30, 60 and 90%).

Table 42. Stress relaxation in the cold-drawn wire with a diameter of 4.5 mm made of steel 1Kh18N9T [206].

(1) σ_0 при 20°C, МН/м² (кГ/мм²)	Температура, °C	(3) σ_0 , МН/м² (кГ/мм²)	(4) σ_t , МН/м² (кГ/мм²), за время, ч	
			100	500
1450(145)	385	202(20,2)	184(18,4)	156(15,6)
	420	233(23,3)	128(12,8)	67(6,7)
	450	205(20,5)	59(5,9)	26(2,6)
1600(160)	385	197(19,7)	185(18,5)	156(15,5)
	420	200(20,0)	132(13,2)	73(7,3)
	450	197(19,7)	88(8,8)	26(2,6)

Continuation Table 42.

(1) σ_0 при 20°C, МН/м² (кГ/мм²)	(4) σ_t , МН/м² (кГ/мм²), за время, ч		
	1000	1750	2500
1450(145)	150(15,0)	131(13,1)	112(11,2)
	57(5,7)	43(4,3)	—
	28(2,8)*	—	—
1600(160)	128(12,8)	116(11,6)	104(10,4)
	51(5,1)	47(4,7)	—
	21(2,1)'	—	—

FOOTNOTE 1. After 750 h. ENFOOTNOTE.

Key: (1) — at 20°C, МН/м² (кГ/мм²). (2) . Temperature, °C. (3) . σ_0 , МН/м² (кГ/мм²). (4) . — МН/м² (кГ/мм²), for time, h.

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They are noted the noticeable decrease of resistance of relaxation (in range from 150 to 450°C) with an increase in the degree of reduction, and also the positive role of tempering at temperatures to 400°C (Fig. 106). It should be noted that the duration of relaxation tests in contrast the preceding/previous investigation was here small (15 h).

At higher temperatures (600-850°C) the negative effect of preliminary plastic deformation is noted already with the smaller degrees of work hardening (15-30c/c) that it is confirmed by A. M. Farshin's data for cold-deformed steel 1Kh18N9T (Table 43).

Effect of TMO on the relaxation resistance of alloy KhN67VMYu on nickel basis is investigated by M. L. Bernstein and E. L. Sitnikova [200]. These authors studied the influence of the degree of deformation and conditions/modes of aging on value residue/settlings (during compression) of the coiled springs with a diameter of 12.7 mm, manufactured from drawn wire of the alloy indicated with different degrees of reduction. At 500°C and $\sigma_0=600-800 \text{ MN/m}^2$ (60-80 kg/mm²) the smallest upsetting (12c/o after 25 h) was observed after 50c/o reduction with the subsequent aging for 6 h with 600-650°C, while at 600°C (20c/o after 25 h) - after 25c/o reduction and aging 6 h at 750°C.

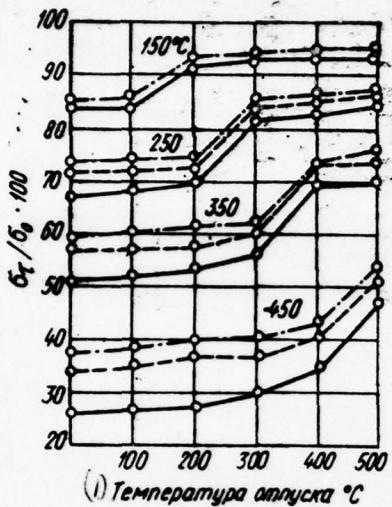


Fig. 106. Effect of work hardening and temperature of tempering on value σ_r/σ_0 at the temperatures indicated: dotted-dash curves - deformation 30%; dashed 60%; solid 90%.

Key: (1). Temperature of relaxation, °C.

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In practice the application/use of FMC for heat-resistant alloys under conditions of relaxation is connected with further accumulation of the experimental data which will make it possible to construct real curve/graphs according to the type of diagram Fig. 104¹.

FOOTNOTE 1. Here are not examined relaxation-resistant alloys on

copper basis, hardened by TMC. Some data on the effect of plastic deformation and subsequent low-temperature annealing on the relaxation resistance of such alloys are given in work [142].

ENDFOOTNOTE.

4. Structural transformations in the process of stress relaxation.

The role of the structural transformations, which occur in the process of stress relaxation at high temperatures, is most convenient to examine on austenitic steels and nickel-chromium alloys, since in these materials, which usually relate to a number dispersive hardening, are possible the diverse variants of structural transformations. So, during prolonged heating in the specific temperature interval was preliminarily hardened, and in the majority of the cases and tempered steel are separated excess phases from solid solution (carbide or intermetallic), but previously separated metastable phases transfer/convert into more stable structural state. In some austenitic steels, as already mentioned above, under the effect of temperature was feasible the partial decomposition of solid solution, connected with allotropic change $\gamma \rightarrow \alpha$, $\gamma \rightarrow \sigma$, $\alpha \rightarrow \sigma$.

Table 43. Effect of the degree of work hardening ϵ on the relaxation resistance of cold-worked steel 1Kh18N9T [208].

(1) Темпера- тура ис- пытания, °C	(2) σ_{τ} , MN/m ² ($\kappa\Gamma/\text{мм}^2$), при ϵ , %		
	10	20	30
700	230—350 (25—35)	50—150 (5—15)	40—100 (4—10)
750	50—100 (5—10)	20—30 (2—3)	5—10 (0,5—1,0)
800	10—50 (1—5)	3—5 (0,3—0,5)	2—3 (0,2—0,3)
850	3—5 (0,3—0,5)	1—3 (0,1—0,3)	1—2 (0,1—0,2)
900	~1 (~0,1)	~1 (~0,1)	~1 (~0,1)

Key: (1) • Testing temperature, °C. (2) • — MN/m² (kg/mm²), when ϵ , o/c.

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These transformations in austenitic steels can occur, also, in the process of creep or stress relaxation at high temperatures (in spite of the preliminary stabilizing tempering).

Since the enumerated phenomena are accompanied by volume change, this can be reflected in the process of the relaxation when the length of part or specimen/sample must remain constant. There is special interest in effect on relaxation of stresses of the structural transformations, connected with the decrease of volume. In this case the increase of the stress because of a decrease in the length of rod (as a result of the decrease of volume) can exceed the voltage drop in the process of relaxation. As a result the effective

stress in the course of time grows/rises (negative relaxation or accumulation of stresses).

This phenomenon in austenitic steels and in different alloys was observed by a number of researchers [11, p. 127; 209, 210]. For the example to Fig. 107, are given, on data of Aleshkin [211], the curves of stress relaxation in steel 1Kh18N9. here the phenomenon of negative relaxation is observed at 700-800°C in connection with the intense isclation of carbides from austenite.

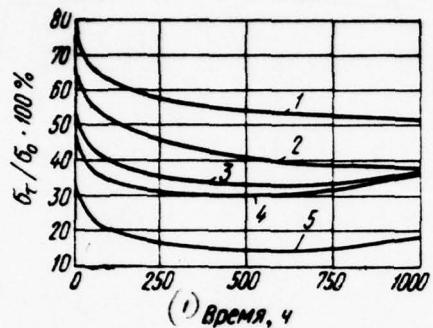


Fig. 107.

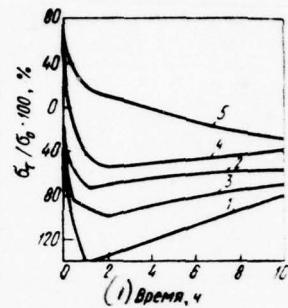


Fig. 108.

Fig. 107. Curves the relative stress of relaxation - time for steel 1Kh18N9 at different temperatures, °C: 1 - 600; 2 - 650; 3 - 700; 4 - 750; 5 - 800.

Key: (1). Time, h.

Fig. 108. Curves relative stress - time for beryllium bronze Br.B2 at 300°C after quenching (1) and tempering at temperatures, °C: 2 - 100; 3 - 150; 4 - 200; 5 - 250 [210].

Key: (1). Time, h.

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Structural transformations at the elevated temperatures in nonferrous alloys in certain cases also lead to negative relaxation, which was observed, for example, in beryllium bronze (Fig. 108) at 300-400°C [210], bronze KMtsZ-1 - at 200-300°C [24], in aluminum alloy with 10% Mg - with 125°C [209], etc.

However, far not in all cases negative volume effect will affect similarly the primary curves stress - time. It is necessary to also take into consideration the relative heat resistance of basement structure solid solution and the releasing phase, and also its quantity, form and size/dimensions or the separated particles. For example, finely dispersed carbides, increasing resistance of relaxation, will act in the same direction, what decrease of the volume of metal, but with coagulated isolation, which weaken steel, are analogous with an increase in the volume.

Further, assuming that phase α and σ under conditions of relaxation (just as during creep) they have smaller refractoriness than γ -solid solution, then with the sufficiently high content of these phases in the structure of alloy the voltage drop as a result of relaxation can exceed the increase of stress, connected with the decrease of volume. As a result relaxation curve will take the form, shown on Fig. 3, where section c-d answers the relaxation softening of metal.

By a specific example can serve the series of nichrome-manganese steels, inclined to the formation of σ -phase in the process of prolonged heating with 650°C , investigated by Ya. S. Gintsburg [24]. On data [212, 213], the transformation $\alpha \rightarrow \epsilon$ occurs with the decrease of volume. Nevertheless, primary the curves of the relaxation of these steels are bent not upwards (as on Fig. 1(7), but downward (according to type curve 2 on Fig. 3), which indicates the sharp relaxation softening of steel as a result of formation in the structure of considerable quantities of σ -phase. The similar phenomena can be observed when during relaxation process at the appropriate temperature begins intense precipitation of the excess phases, which possess the lowered/reduced heat resistance.

Those examined cases can be qualified as anomalous. Of virtually used for hot fastening austenitic steels, as a rule, have sufficiently stable solid solution and allotropic changes usually they are absent.

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In the conditions of high-temperature relaxation, structural changes in such steels are limited to isolation from the solid solution of

secondary phases - carbide or intermetallic. With the impossibility to completely remove internal transformations in alloys in a series of cases it is possible they to utilize for an increase in the prolonged relaxation life and heat resistance.

For an example let us give austenitic heat-resistant steel Rh15Ni25V4T (EI164). In the process of relaxation test with 680-700°C in the structure of hardened and tempered at 750°C steel, continuously occurs the additional formation of secondary phases (in essence Ni₃Ti). Since the particles of this intermetallic at the temperature indicated are separated from the solid solution in sufficiently dispersed form, they take the process of relaxation and primary curves (Fig. 109a) reflect a monotonic voltage drop.

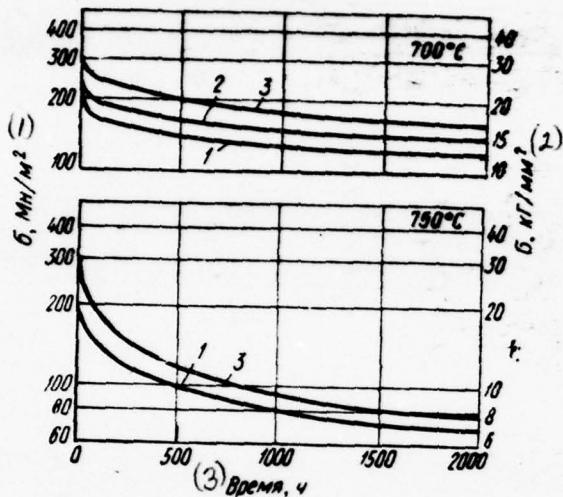


Fig. 109. Primary the curves of the relaxation of steel Kh15N25V4T at 700°C, 750°C and σ_0 , MN/mm² (kg/mm²): 1 - 200(20); 2 - 250(25); 3 - 300(30).

Key: (1). MN/mm². (2). kg/mm². (3). Time, h.

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With an increase in the temperature to 750°C, the structural transformations of steel Kh15N25V4T during prolonged heating have more complex character. As it was shown by Yu. V. Latyshev [214], phase $\beta=\text{Ni}_3\text{Ti}$ (with cubic lattice) partially degenerates itself during phase $\eta=\text{Ni}_3\text{Ti}$ (with hexagonal lattice). After 5000 h begins the process of the re-solution of phase Ni_3Ti whose quantity after

10,000 h is decreased almost to initial (fig. 10). Simultaneously in structure continuously is formed the intermetallic compound Fe_2W (type of the phases of laves), which compensates for "lack" in phase Ni_3Ti . Thus, the total content of intermetallide phases in steel after 5000-10000 h not only is not decreased, but even insignificantly it grows/rises (from 4.9 to 5.35%) . A quantity of phase Ni_3Ti for the same time decreased from ~4 to 2%, while a quantity of phase Fe_2W , on the contrary, increased to 3.3%.

The described transformations contribute to the preservation/retention/maintaining the resistance to creep at a sufficient level even at so high a for steel of this class temperature as 750°C. However, under conditions of stress relaxation, the replacement of phase Ni_3Ti by phase Fe_2W only somewhat brakes the softening of steel at temperature of 750°C. After 1000 h the remaining stress composes a total of 35-40% of the initial (see Fig. 109b). It is possible to assume that the structural instability of the datum of steel with 750°C is under conditions of relaxation negative factor.

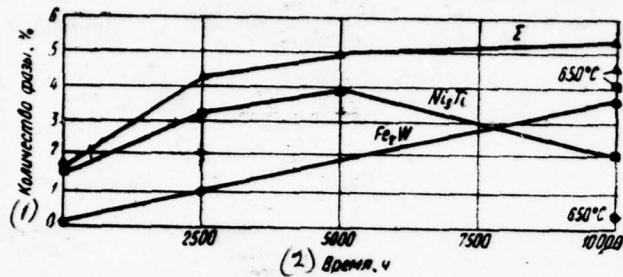


Fig. 110. Change of the quantity of strengthened/hardened phases in the structure of steel Kh15N25V5T in dependence on the time of testing with 750°C (Σ —total curve).

Key: (1). Quantity of phase, o/o. (2). Time, h.

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Interesting results gave unique in duration relaxation test of the heat-resistant alloy Kh15N65VMTYu on nickel-chromium basis. Alloy was tested for relaxation with 750°C for 20000 h with the initial stresses, composing 33, 40, 50 and 60% from the average value of the yield point of alloy at the same temperature of 600 MN/m² (60 kg/mm²). Heat treatment consisted of quenching at 1180°C in air and tempering for 16 h at 800°C.

From the examination of the primary curves of relaxation (Fig.

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111) it is evident that the curves for different initial stresses similar and reflect two relaxation times of stresses. The first period (by duration (300-500 h) is characterized by a sharp voltage drop at all values σ_0 .

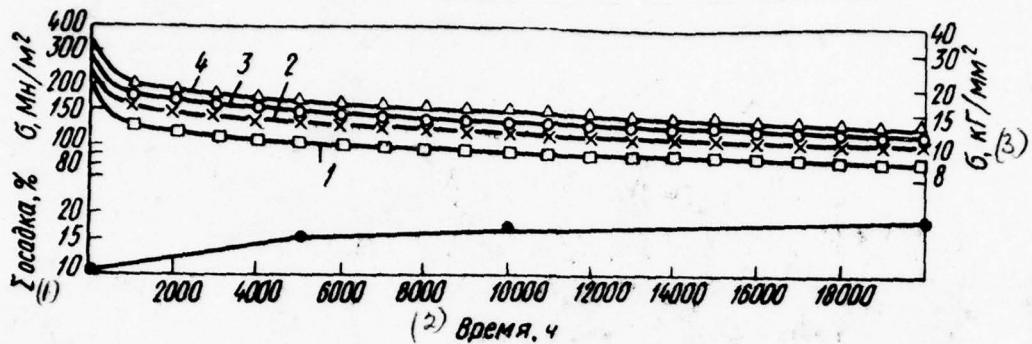


Fig. 111. Primary the curves of the relaxation of alloy Kh15N65MTYu at 750°C and a change in the content of the strengthened/hardened phase (lower curve) σ_0 , MN/mm² (kg/mm²): 1 - 200(20); 2 - 250(25); 3 - 300(30); 4 - 350(35).

Key: (1). Σ residue/settling, о/c. о, MN/mm². (2). Time, h. (3). σ , kg/mm².

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Toward the end of I periods, the remaining stress is $\sim 0.7\sigma_0$, and the average speed of relaxaticr for different values σ_0 varies from 0.02 to 0.05 MN/mm² (0.002-0.005 kg/mm²) in hour (or from 0.01 to 0.02 о/c/h). Then begins II period, which is characterized by the smaller intensity of stress relaxation. Already during the first stage of this period (1000-2000 h) the rate of relaxation becomes 4-5

times less than at the end of 1 perious, and it continues noticeably to be decreased approximately to 5000 h. In the interval of 5000-20,000 h, stress relaxation occur/fiow/lasts with considerably lower speed (0.001-0.003 cyc h).

Specially carried out studies [215] showed that the prolonged heating KnN65VMTYu at 750°C, in spite of the preceded stabilizing tempering, causes the additional isclation of an excess phase of the type Ni₃(TiAl), that is accompanied by the partial redistribution of cell/elements between the solid solution and the excess phase (Table 44).

Table 44. Distribution of the alloying elements, o/c in alloy Sh15N65VMTYu between the solid solution and the strengthened/hardened phase.

(1) Режим обработки ¹	Cr	Ni	W	Mo	Ti	Al	Si	Fe
(2) Упрочняющая фаза								
(3) Твердый раствор								
800°C, 12 ⁴ _③	3,1	10,8	7,0	6,4	44,7	36,5	16,6	17,2
750°C, 5000 ⁴ _③	1,0	17,7	10,0	7,1	76,6	64,0	16,6	17,2
750°C, 10000 ⁴ _③	2,5	19,1	11,5	5,9	87,3	60,9	16,6	17,2
750°C, 20000 ⁴ _③	2,7	19,7	15,0	6,2	79,3	39,1	16,6	17,2
800°C, 5000 ⁴ _③	1,2	13,1	10,0	5,9	60,0	46,2	16,6	17,2
800°C, 10000 ⁴ _③	1,9	14,8	10,0	8,1	70,7	53,0	16,6	17,2
800°C, 20000 ⁴ _③	1,6	18,8	13,0	13,8	88,6	48,1	16,6	17,2

Key: (1). Conditions/mode of treatment¹.

FOOTNOTE 1. Previous treatment: quenching with 1180°C, cooling in air. ENDFOOTNOTE.

(2). Strengthened/hardened phase. (3). h. (4). Solid solution.

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If in initial state a quantity of latter occupies ~100/o that after

5000 h (at 750°C) it grows/rises to 15.4% (Fig. 112). Subsequently the intensity of the isolation of phase Ni₃(TiAl) noticeably weakens; 77% of additionally separated quantity of this phase fall on first 5000 h of aging with 750°C and only 23% - to subsequent 15,000 h. The continuous fading of the process of relaxation of stresses of the investigated alloy is connected with the gradual stabilization of structure and, in particular, with the curtailment of the impoverishment of solid solution by nickel and aluminum, which is confirmed by the data of phase-shift analysis (Table 44).

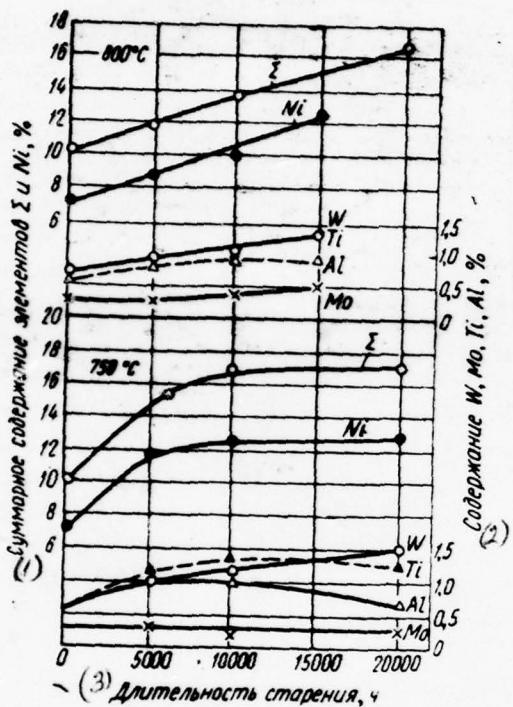


Fig. 112. Change in the total quantity (Σ) and of the composition of the strengthened/hardened phase in the structure of alloy Kh15No5VMTYu in dependence on the duration of aging.

Key: (1). Total content of cell/elements Σ and Ni, o/o. (2). Content W, Mo, Ti, Al, c/c. (3). Duration of aging, h.

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Apparently, the stabilization of the structure of alloys with the

heavily alloyed solid solution has positive effect on prolonged relaxation life. About the fact that strengthening the solid solution in a series of cases of more effective than creation in the structure excessive quantity of particles of the excess phase, speak the results of comparative test for relaxation at 800°C two nickel-chromium alloys of which one had the heavily alloyed solid solution and the moderate quantity of secondary (strengthening) phase, but the second - less alloyed solid solution, but a considerably larger quantity of that strengthened/hardened phase [215]. During first hundred of hours, both of alloys had virtually identical relaxation life, but after 1000 h the level of the remaining stresses in the second alloy was below.

On the basis of that presented, it is possible to conclude that the structural transformations, which occur in alloys during the temperature conditions of stress relaxation, have specific effect on the course of the process of relaxation. The effect of age hardening or allotropic changes is applied on the purely relaxation phenomena; therefore the common picture of process noticeably becomes complicated.

In connection with this logically arises the "reverse" question: can the process of high-temperature relaxation of stresses (not leading to decomposition) have in turn, specific effect on the

structure of tested steel (cr alloy).

Austenitic steels of brands 1Kh18N9T, 1Kh14N18V2BR and Kh20N25VM3M, and also alloy KhN77TYu were tested for stress relaxation at temperature of 650°C, approximately corresponding to temperature 0.5 $T_{m\alpha}$. The selected initial stresses in all cases were below yield point, comprising $\sigma_0 = (0.4-0.6) \sigma_{0.2}$.

The specimen/samples, tested for stress relaxation for 2000 h, subjected to microscopic, electron-microscope, phase, chemical and X-ray structural analyses [216]. They in parallel investigated specimen/samples in the initial state, and also after heating of the same duration and to temperature (with $\sigma_0 = 0$), which made it possible to separate/liberate the temperature effect of testing from the effect of the very process of relaxation.

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Since as different initial microstructures of austenitic steel they can possess dissimilar receptivity to the possible effect of the process of stress relaxation, the annular specimen/samples prior to tests were subjected to six versions of the heat treatment (see Table 39), which made it possible to investigate each steel in six structural states. The latter were characterized by a size of the

grain of solid solution, a quantity of excess phase and a degree of its dispersity.

Table 45 gives quantities of separated phases after initial heat treatment, relaxation tests and prolonged heating with $\sigma_0=0$. These data, and also results of microexamination indicate that the structural changes, discovered in the specimen/samples, tested for relaxation, are analogous to the changes in the structure of the specimen/samples, subjected isochronous heating in the unloaded state.

Table 45. Quantity of secondary phases in steels and alloys in different states.

(1) Состояние	(2) Количество фаз, %, в зависимости от температуры закалки, °C, сталей							
	1X18H9T		1X14H18B2БР		X20H25ВМ3Б		ХН77ТЮ	
	1050	1200	1000	1250	1000	1200	950	1080
(3) Исходное состояние								
(4) Закалка	0,4	0,3	0,9	0,5	1,9	1,1	1,1	1,4
(5) То же+отпуск при 750°C	0,8	0,6	1,0	1,3	3,0	2,1	9,0	9,4
(6) То же, 800°C	0,9	1,2	1,2	1,5	2,2	1,4	8,0	8,9
(7) Нагрев при 650°C, 2000 ч	0,8	0,85	1,4	1,3	8,0	2,5	12,6	12,7
(8) Испытание на релаксацию								
(9) Закалка	1,0	0,9	1,4	1,5	7,7	2,0	12,3	12,6
(10) То же+отпуск при 750°C	0,7	0,95	1,5	1,6	7,0	3,0	13,3	12,7
(11) То же, 800°C	0,9	0,7	1,3	1,6	4,8	2,6	13,7	13,1

Key: (1). State. (2). Quantity of phases, c/o, depending on temperature of quenching, °C, steels. (3). Initial state. (4). Quenching. (5). The same + tempering with 750°C. (6). The same, 800°C. (7). Heating at 650°C, 2000 h. (8). Relaxation test.

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Thus, was not revealed the effects of the process of relaxation on the microstructure of austenitic steels (with carbide and intermetallic strengthening) and of heat-resistant nickel-chromium alloy after different heat treatments. The obtained experimental data

speak about the absence of the dependence of a quantity of excess phases in structure and character of their distribution on the applied stresses. However, it is necessary to note comparatively high temperature of testing, close to $0.5 T_{m\alpha}$, with which diffusion processes proceed sufficiently intensely. At less high homologous temperatures, for example ($0.3-0.4 T_{m\alpha}$) is possible fundamentally different picture. The higher level of initial and, therefore, remaining stresses also can lead to other results, in particular at the initial stages of the process of relaxation.

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Appendix.

PROGRAM FOR THE CALCULATION OF RELAXATION CURVES ACCORDING TO THE HYPOTHESIS OF FLOW WITH THE STRUCTURAL PARAMETER.

Present program is comprised for the calculated determination of the curves of stress relaxation at constant temperatures on the basis of the characteristics of the creep of the material, found in experiments with constant stresses.

The program of calculation is instituted on the use of characteristics of the creep of the material, obtained in experiments at constant stresses and temperatures and approximated by the expression

$$\epsilon_n = \bar{A}\sigma^k [1 - \exp(-\bar{C}\sigma^l \tau)] S + \bar{B}\sigma^m \tau, \quad (1)$$

where ϵ_n - deformation of creep;

σ - stresses

τ - time;

$\bar{A}, \bar{B}, \bar{C}, \kappa, l, m$ - constant of material, \bar{A}, \bar{B}, k and m changing their values for $\sigma > \sigma_{np}$ and $\sigma < \sigma_{np}$ (where $\sigma_{np} = \text{const}$);

S - function of the structural parameter as which is accepted maximum preliminary instantaneous plastic deformation ϵ_{nn}^0 .

Is utilized the following expression for S , instituted on test results for short-term creep for constant stresses and variable values of the preliminary plastic deformation:

$$S = 1 + h(\epsilon_{nn}^0 - \epsilon_{nn})^q, \quad (2)$$

where h and q - constant;

$\epsilon_{nn} = f(\sigma)$ - plastic deformation, which corresponds to stress σ according to instantaneous stress-strain diagram. After accepting the approximation of stress-strains curve in the form

$$\epsilon = \frac{\sigma}{E} + r \left(\frac{\sigma}{\sigma_y} \right)^p, \quad (3)$$

where r , p - constant;

E - modulus of elasticity;

σ_y - elastic limit,

we will obtain

$$S = 1 + hr^q \left\{ \left(\frac{\sigma_{max}}{\sigma_y} \right)^p - \left(\frac{\sigma}{\sigma_y} \right)^p \right\}^q. \quad (4)$$

Constants \bar{A} , \bar{B} , \bar{C} , k , b , c determine as follows:

1. Are determined values of a , b , c according to the diagram, presented in Fig. 1, where

$$b = \operatorname{tg} \alpha, \quad c = \frac{1}{\tau_m} \ln \frac{a}{b\tau_m}.$$

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2. In dual logarithmic coordinates are constructed dependences of values a , b , c from stress (Fig. 2). Through slope/inclination and position of curves, find the values of constants for $\sigma < \sigma_{np}$ from

$$a = \bar{A}\sigma^k = 10^{a_1}\sigma^{k_1}; \quad b = \bar{B}\sigma^m = 10^{b_1}\sigma^{m_1};$$

$$c = \bar{C}\sigma^l = 10^{c_1}\sigma^l$$

for

$$\sigma > \sigma_{np} \text{ from}$$

$$a = 10^{a_2}\sigma^{k_2}; \quad b = 10^{b_2}\sigma^{m_2}; \quad c = 10^{c_2}\sigma^l,$$

and also the value of stress σ_{np} , with which the straight lines with different slope/inclination they intersect.

Constants h and q calculate according to the curves of creep, obtained at $\sigma=\text{const}$ and the different values of plastic strain ϵ_{pl} , those approximated by the dependence

$$\epsilon_n = \epsilon_{n_0} [1 + h(\epsilon_{n_0})^q], \quad (5)$$

where ϵ_{n_0} - creep strain when $\epsilon_{n_0}=0$.

The mentioned above constants of material are the function of temperature (their values are determined with those temperatures at

which were conducted the experiments).

Differentiating expression (1), we will obtain the dependences of creep rate with constant stresses from the time:

$$\dot{\epsilon}_n = \bar{A} \bar{C} \sigma^{k+l} \exp(-\bar{C} \sigma^l \tau) S + \bar{B} \sigma^m. \quad (6)$$

Is utilized the hypothesis of flow with the structural parameter as which is accepted the amount of instantaneus preliminary plastic deformation.

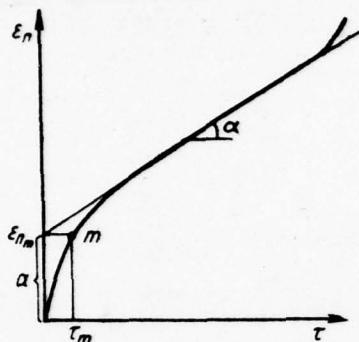


Fig. 1. Determination of coefficients of a , b and c .

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Calculation is instituted on the integration of the differential equation of stress relaxation in the specimen/sample of the constant length:

$$\frac{d\sigma}{d\tau} = -E\dot{\epsilon}_n(\sigma, \tau, \epsilon_{nn}^0) \quad (7)$$

under initial conditions $\tau=0$, $\sigma=\sigma_0$,

where $\dot{\epsilon}_n$ rate of creep, assigned/prescribed by analytical expression (6).

Program is comprised on language "ALGOL-60" for ETsVM [digital computer] BESM-2 and BESM-3M and is instituted on the numerical integration of equation (7) during the use of expressions (6) and (4) by Runge-Kutta's method. Program makes it possible to calculate the values of residual stress at several values of time by the common/general/total duration of 1 h for single and repeated stretchings at several values of initial stress.

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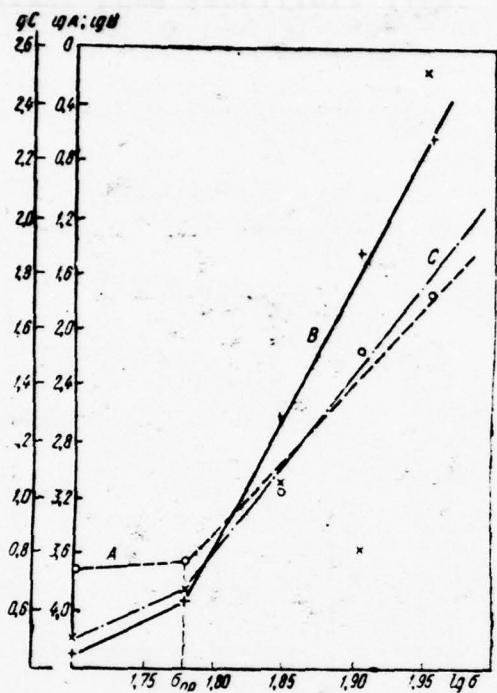


Fig. 2. Dependence of coefficients A, B and C on stress for the alloy E1827.

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For this, is introduced the following numerical material:

1. BEGIN INTEGER MP, MM, J, JJ, M5, K3;
2. REAL SIGMA, A1, A2, B1, B2, C1, H1, R1, U, E1, L, P,
3. Q, K1, K2, M1, M2, SII, DS1, SIGMA2;
4. READ (MP, MM, A1, A2, B1, B2, C1, H1, R1, U, E1,
5. L, P, Q, K1, K2, M1, M2, SII, DS1, SIGMA2);
6. READ (M5);
7. BEGIN
8. ARRAY SIGMA5 (1 : MM), T, X(0 : 2×MP-1), T1, X1(0 : 5);
9. PRINT (MP, MM, A1, A2, B1, B2, C1, H1, R1, U, E1,
10. L, P, Q, K1, K2, M1, M2, SII, DS1, SIGMA2);
11. BEGIN REAL PROCEDURE F(T2, X2); VALUE
T2, X2;
12. REAL T2, X2; BEGIN REAL A, B, C, AA, BB, M, K;
13. REAL X3, X4, X5;

№ (a)	Значения параметра (b)	Обозначение (c)
1	Шаг интегрирования	MP
2	Число значений начального напряжения	MM
3	Значение показателя степени $\bar{A}=10^{a1}$ для $\sigma < \sigma_{\text{пр}}$	A1
4	» » » $\bar{A}=10^{a2}$ для $\sigma \geq \sigma_{\text{пр}}$	A2
5	» » » $B=10^{b1}$ для $\sigma < \sigma_{\text{пр}}$	B1
6	» » » $\bar{B}=10^{b2}$ для $\sigma \geq \sigma_{\text{пр}}$	B2
7	» » » $\bar{C}=10^{c1}$	C1
8	Значение h	H1
9	Значение r	R1
10	Значение предела упругости σ_y	U
11	Значение модуля упругости E	E1
12	Значение l	L
13	Значение p в выражении (4)	P
14	» q в выражении (4)	Q
15	» k при $\sigma < \sigma_{\text{пр}}$	K1
16	» k при $\sigma \geq \sigma_{\text{пр}}$	K2
17	» m при $\sigma < \sigma_{\text{пр}}$	M1
18	» m при $\sigma \geq \sigma_{\text{пр}}$	M2
19	Первое значение начального напряжения σ_0	S11
20	Разница между значениями начального напряжения	DS1
21	Значение $\sigma_{\text{пр}}$	SIGMA2
22	Число подтягов	M5°

Key: (a). pp. (b). Values of parameter. (c). Designation. (1).

Step/pitch of integration. (2). Number of values of initial stress.

(3). Value of exponent ... for (4). for. (5). for. (6). for. (7).

[none]. (8). Value. (9). Value. (10). Value of elastic limit. (11).

Value of module/modulus of elasticity. (12). Value. (13). Value p in expression (4). (14). in expression (4). (15). with. (16). with.

(17). with. (18). with. (19). first value of initial stress a (20).

Difference between values of initial stress. (21). Value. (22).

Number of stretchings.

ECOTNOTE 1. M5 - is not printed.

When conducting of calculations, is printed:

- a) the introduced numerical material of 1-21 values;
- b) the initial stress, 6 values of time in the portion/fractions of hour and corresponding to them 6 values of residual stress. A number of versions is determined by product $(MM) \times (M5+1)$. Is given below the text of program.

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14. X3 := IF X2>0 THEN (2×X2/U)↑ P ELSE -(-2×X2/U)
   ↑ P;
15. IF(2×SIGMA/U)↑2-X<0 THEN A := I ELSE;
16. A := -1+(H1/2↑(P+Q))×((2×SIGMA/U)↑ P-X3)↑PQ×RI↑Q;
17. IF X2<SIGMA2 THEN BEGIN M := M1; K := K1;
18. AA := A1; BB := B1 END ELSE BEGIN M := M2;
   K := K2;
19. AA := A2; BB := B2 END;
20. X3 := EXP(2.303×CI×L×LN(X2))×(T2+K3);
21. X4 := IF X2<0 THEN O ELSE EXP((K+L)×LN(X2)+2.303×AA+2.303×CI);
22. X5 := IF X2<0 THEN O ELSE EXP(M×LN(X2)+2.303×BB);
23. B := IF X3>40 THEN O ELSE
24. E1×X4×EXP(-X3);
25. C := E1×X5;
26. F := -A×B-C;
27. END F;
28. BEGIN REAL PK1, PK2, PK3, PK4, H; INTEGER I;
29. FOR JJ := 1 STEP 1 UNTIL MM DO SIGMA5(JJ);
30. : = SI 1+(JJ-1)×DSI; JJ=1; SIGMA := SIGMA5(JJ);
31. DLI; K3 := 0;
32. DL := T(O) := 0.0001; X(O) := SIGMA; H := 1/MP↑2;
33. FOR J := 0 STEP 1 UNTIL MP-1 DO BEGIN
34. PK1 := F(T(J), X(J))×H;
35. PK2 := F(T(J)+H/2, X(J)+PK1/2)×H;
36. PK3 := F(T(J)+H/2, X(J)+PK2/2)×H;
37. PK4 := F(T(J)+H, X(J)+PK3)×H; I := J+1;
38. X(I) := X(J)+(PK1+PK2×2+PK3×2+PK4)/6;
39. T(I) := T(J)+H END;
40. H := 1/MP;
41. FOR J := MP STEP 1 UNTIL 2×MP-2 DO BEGIN
42. PK1 := F(T(J), X(J))×H;
43. PK2 := F(T(J)+H/2, X(J)+PK1/2)×H;
44. PK3 := F(T(J)+H/2, X(J)+PK2/2)×H;
45. PK4 := F(T(J)+H, X(J)+PK3)×H; I := J+1;
46. X(I) := X(J)+(PK1+PK2×2+PK3×2+PK4)/6;
47. T(I) := T(J)+H END;
48. T(1) := T(0)+H;
49. PRINT(SIGMA, TI, XI);
50. TI(0) := 0.0001; X1(0) := X(0); T1(1) := T(60);
51. X1(1) := X(60); T1(2) := T(64); X1(2) := X(64);
52. T1(3) := T(74); X1(3) := X(74); T1(4) := T(89);
53. X1(4) := X(89); T1(5) := T(119); X1(5) := X(119);
54. PRINT(SIGMA, TI, XI);
55. IF K3<F5 THEN BEGIN K3 := K3+1; GO TO
56. DL END;
57. IF JJ<MM THEN BEGIN JJ := JJ+1;
58. SIGMA := SIGMA5(JJ); GO TO DL END;
59. END END END END

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